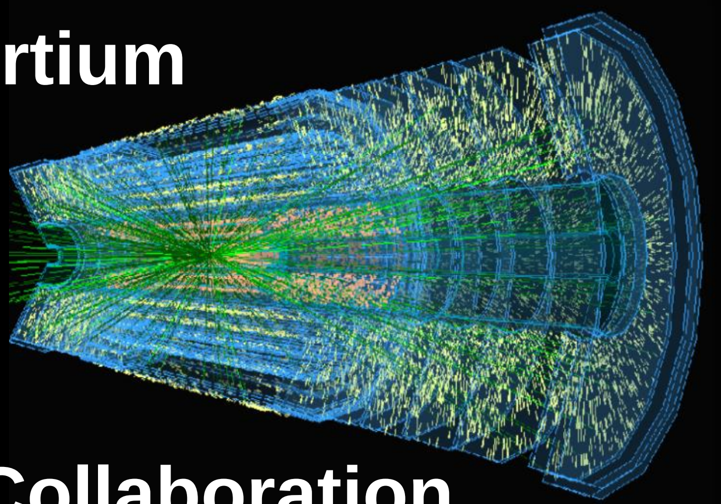
Silicon Tracking Detectors for Hadron Beam Monitoring and Imaging

Phil Allport
(Particle Physics Group, University of Birmingham)
20/01/16

- Introduction to silicon detectors in particle physics
- Some UK examples of applications to hadron therapy
- The Proton Radiotherapy Verification and Dosimetry Applications (PRaVDA) Consortium
  - PRaVDA Concept
  - PRaVDA Strip System
  - PRaVDA Status and Outlook

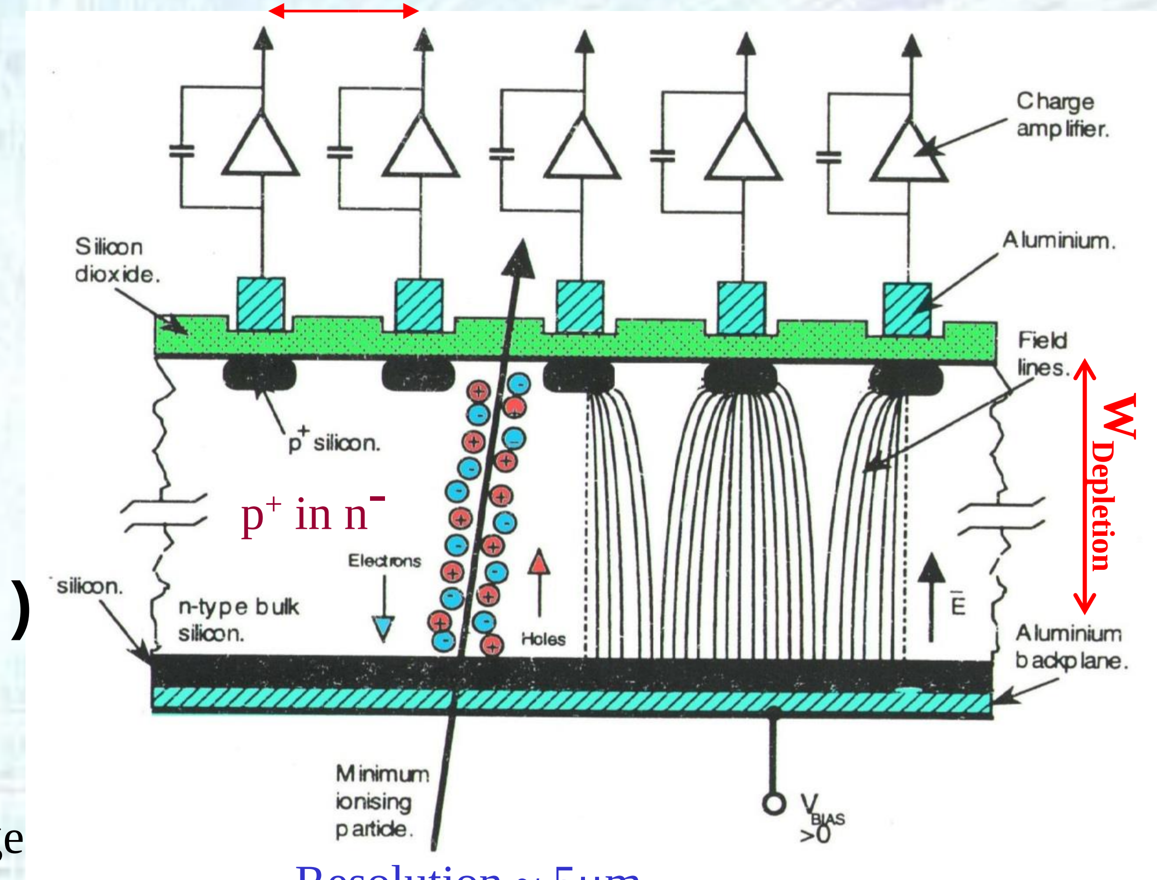


- Recent Results from the pCT Collaboration
- Conclusions

Silicon Detector Trackers in Particle Physics

- Highly segmented silicon detectors have been used in high energy and nuclear physics experiments for over 40 years
- **The principle application has been to detect the passage of ionising radiation with high <u>spatial</u> resolution, fast timing and good efficiency.**

Pitch ~ 50µm



Resolution ~ 5µm

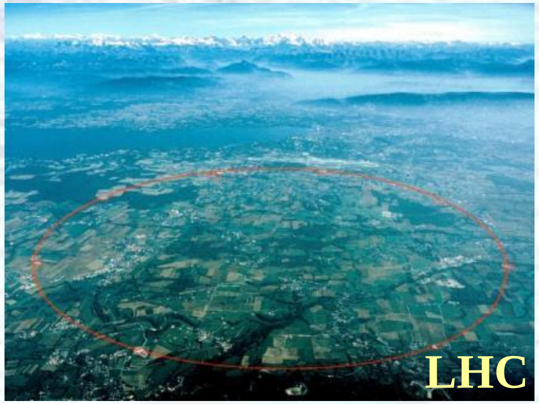
- **Segmentation → position**
- **Depletion depth → efficiency**
- **$(W_{Depletion} = \{2\rho\mu\varepsilon(V_{ext} + V_{bi})\}^{1/2})$**

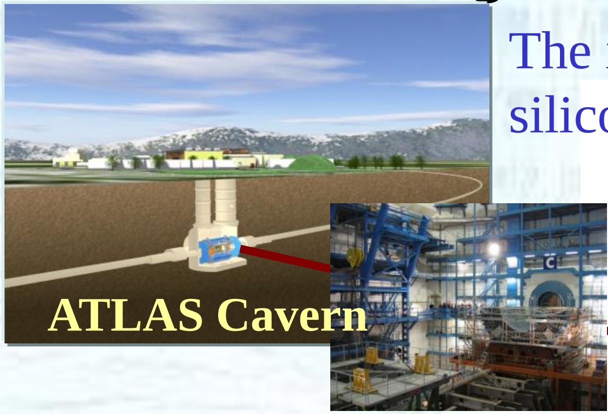
Resistivity | Mobility | Applied Voltage

- **~80e/h pairs/µm produced by passage of minimum ionising particle, 'mip' → signal of 1.3fC per 100µm of depleted detector**
- **Signal collected typically in a few ns (depends on $W_{Depletion}$ and V)**

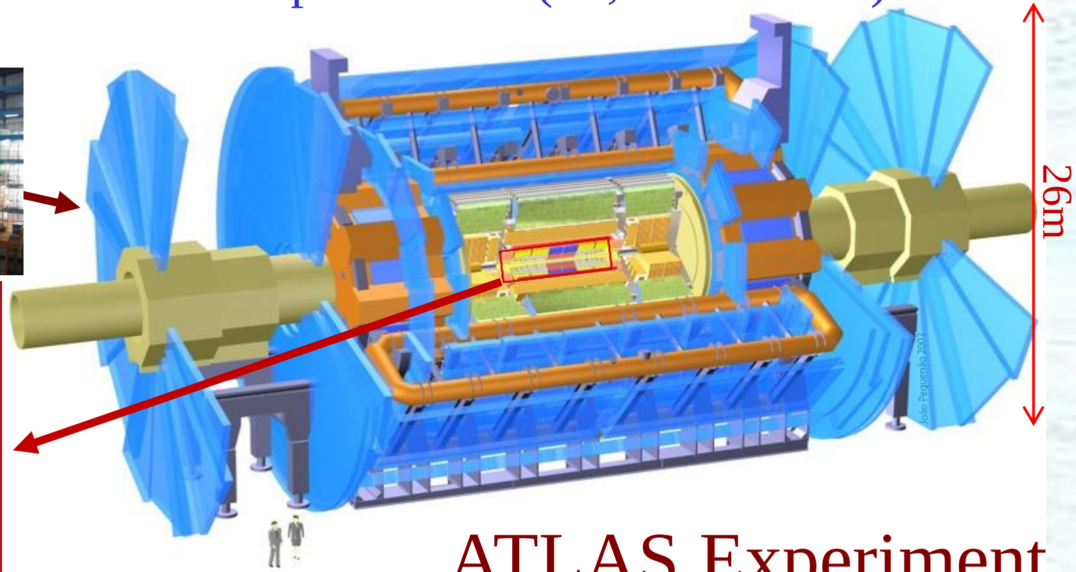
Silicon Detector Trackers in Particle Physics

- **Large areas of silicon detectors for high rate, high radiation environments built for the Large Hadron Collider at CERN**

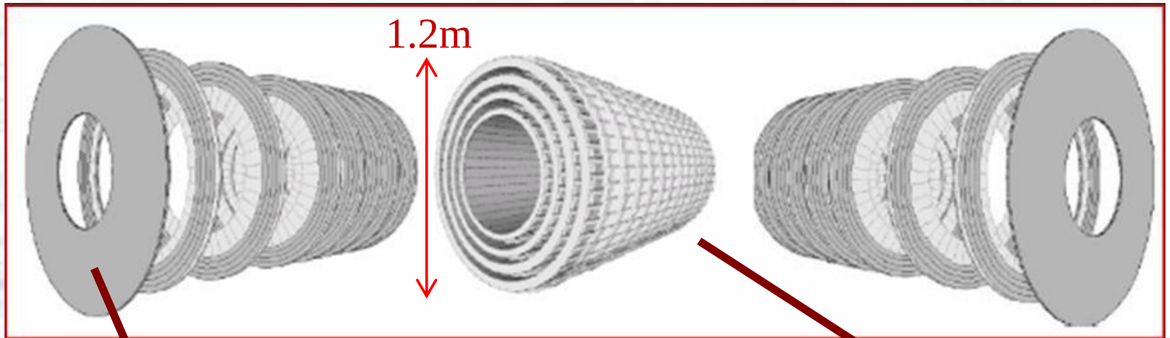


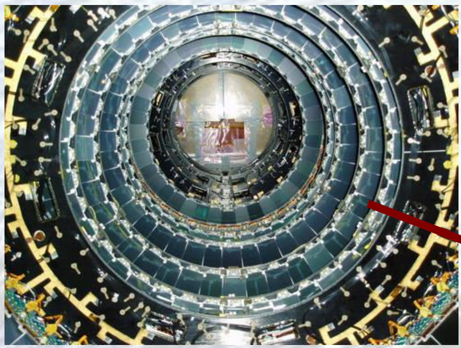


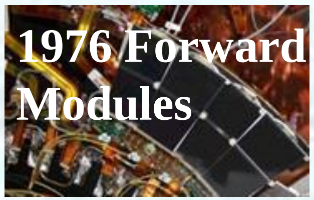
The innermost tracking system has 610,000 cm^2 of silicon micro-strip detectors (17,000 sensors)

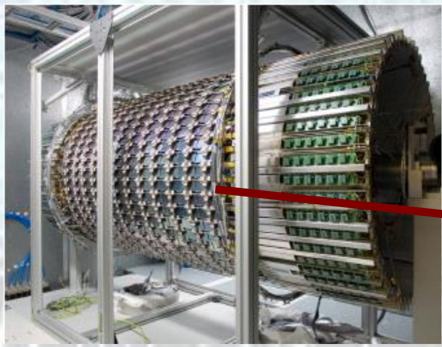


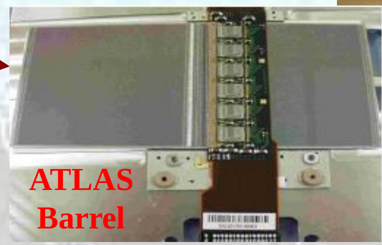
ATLAS Experiment





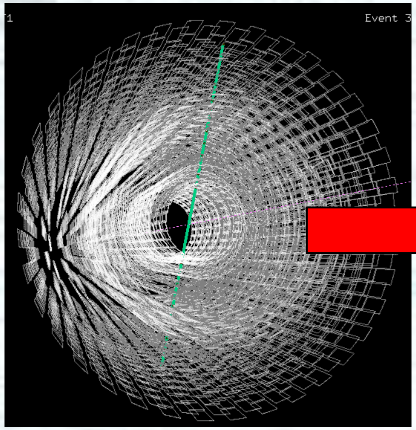




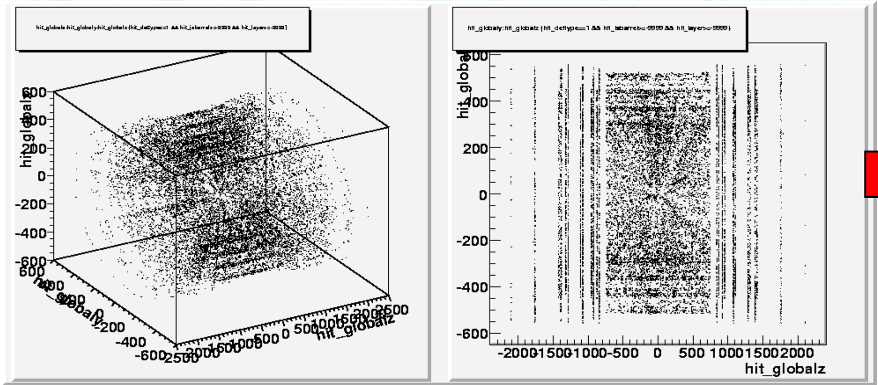


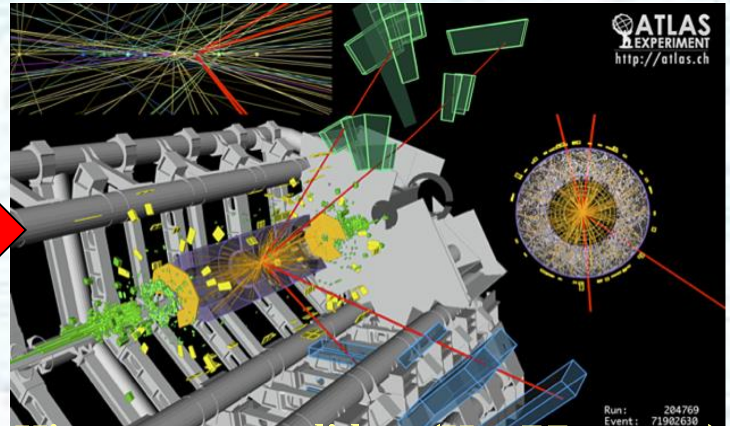
Silicon Detector Trackers in Particle Physics

- **Large areas of silicon detectors for high rate, high radiation environments built for the Large Hadron Collider at CERN**
- **Charged particle tracks found from joining hits in the large arrays of finely segmented silicon detectors**

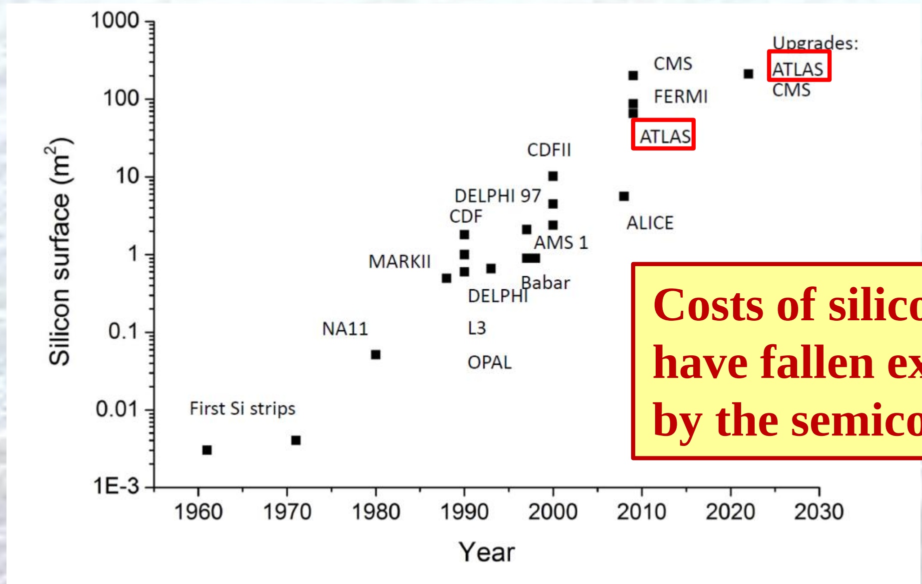


(New image every 25ns but can only store few 100/s)



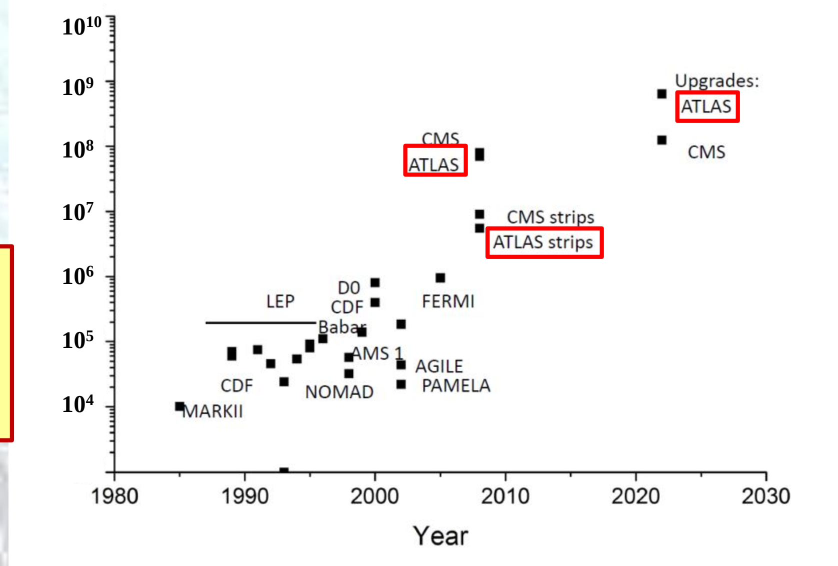


Higgs event candidate (H→ZZ→μμμμ)



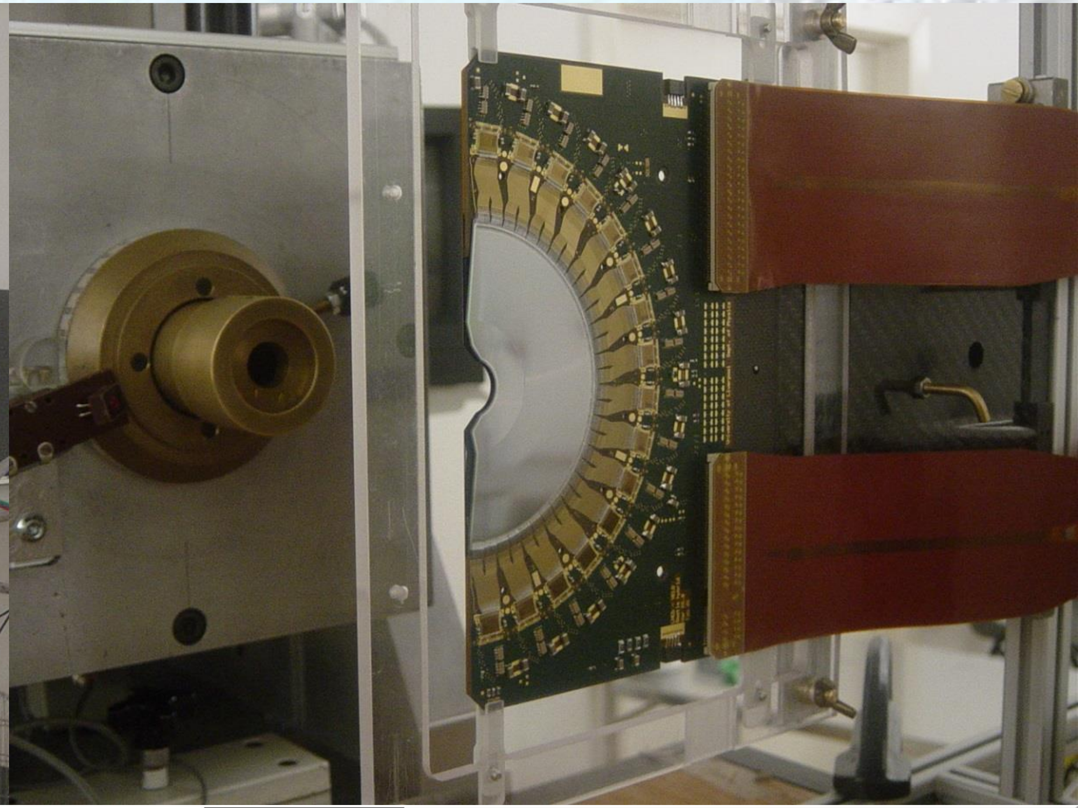
Detector areas and channel numbers grow exponentially

Costs of silicon technologies have fallen exponentially driven by the semiconductor industry

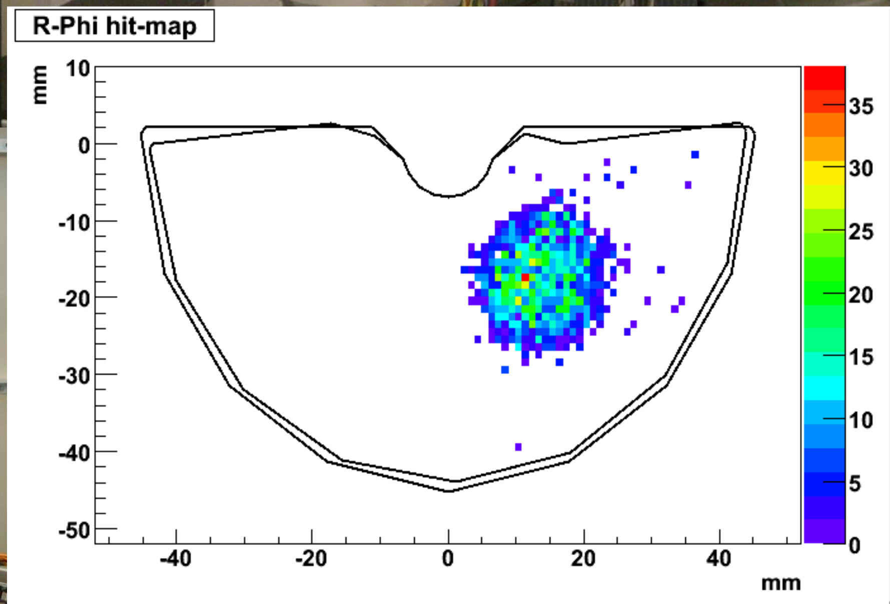


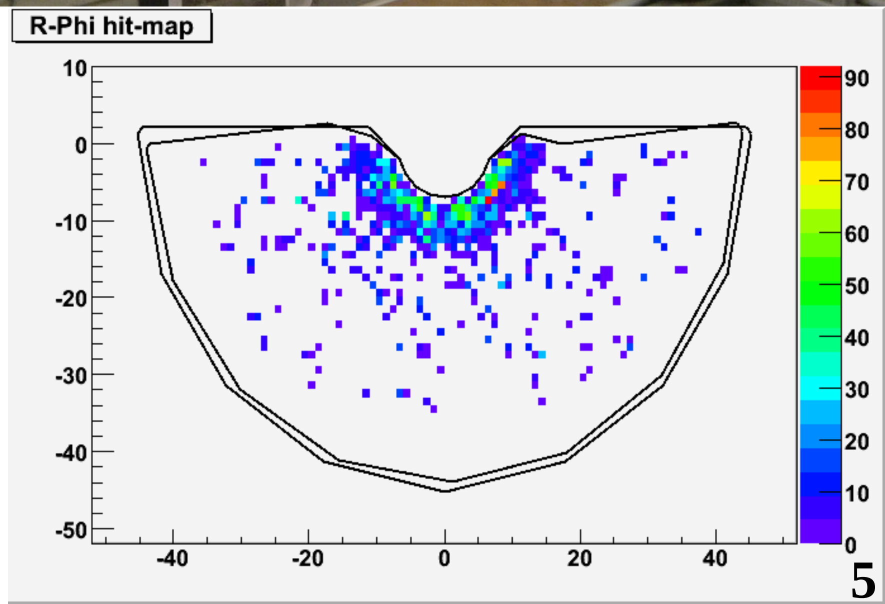
LHCb VeLo Module as Beam Halo Monitor

G. Casse , J. Taylor, T. Smith (Liverpool)
A. Kacperek (Clatterbridge Centre for Oncology Proton Therapy Facility)



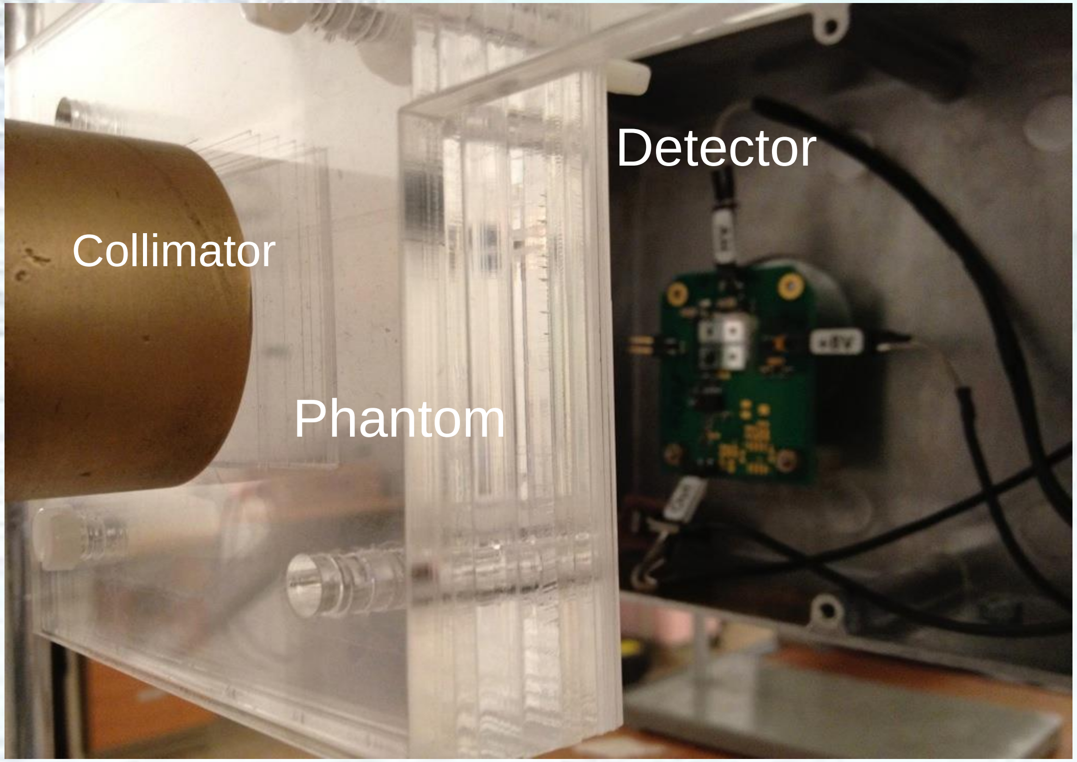
LHCb Vertex Locator (VeLo) assembly at CERN

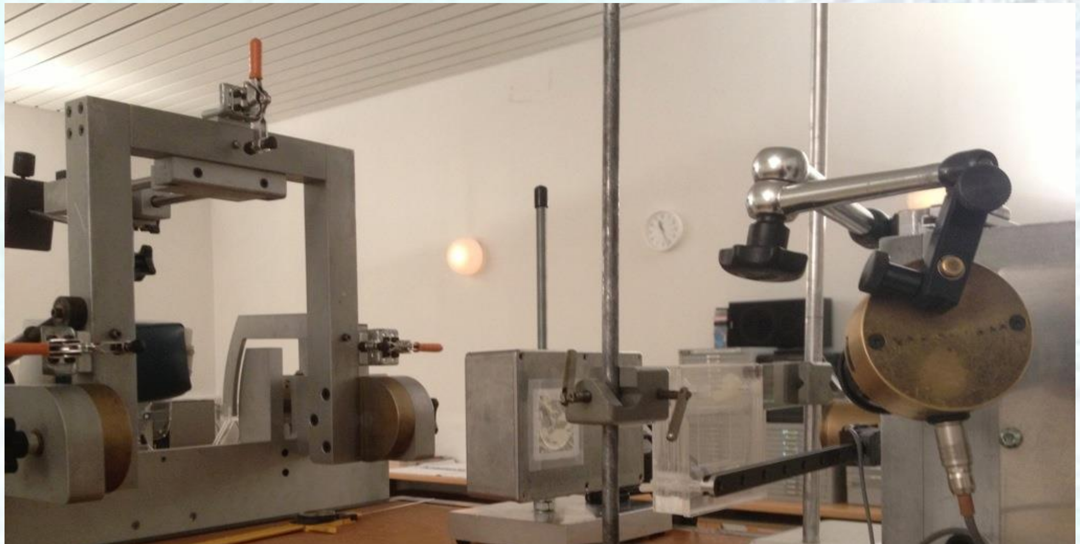


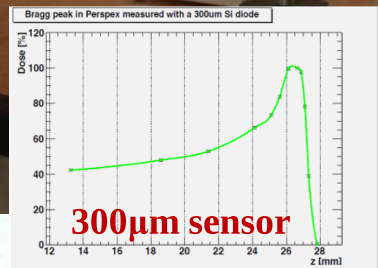


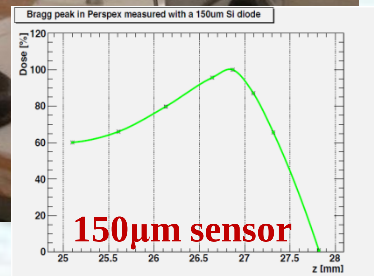
Perspex Phantom Measurement at Clatterbridge

J. Taylor, G. Casse (University of Liverpool); A. Kacperek (Clatterbridge Centre for Oncology)









Initial aim: to reproduce Bragg peak in perspex using n-in-p silicon detectors shown to be radiation hard to MGy doses

Detector system comprised of RD50 n-in-p diode and custom built data acquisition

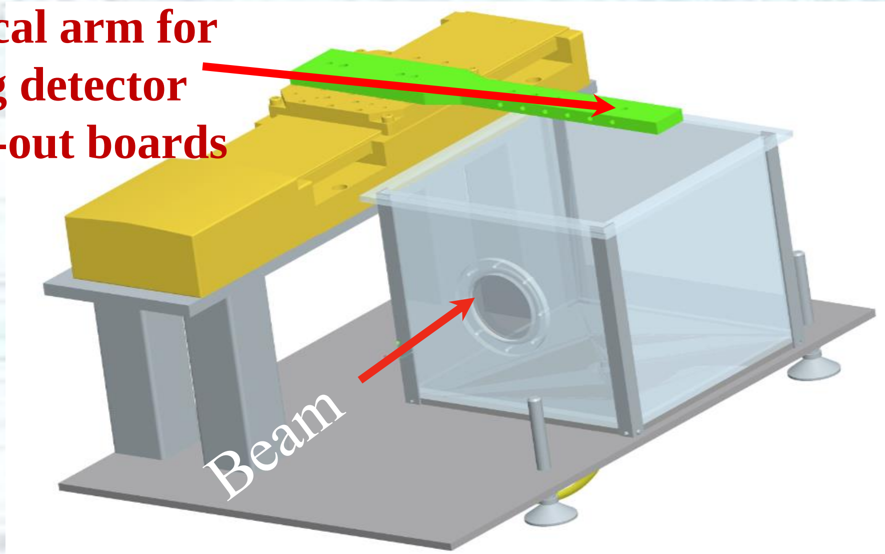
Phantom machined on the laser cutter with sheets of Perspex of varying thickness: 5 - 0.2 mm to allow precise steps to be made

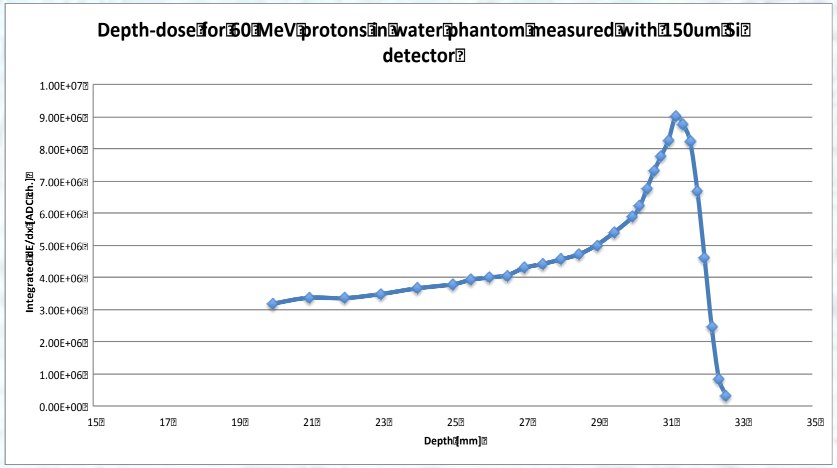
Novel Water Phantom Beam Monitoring System

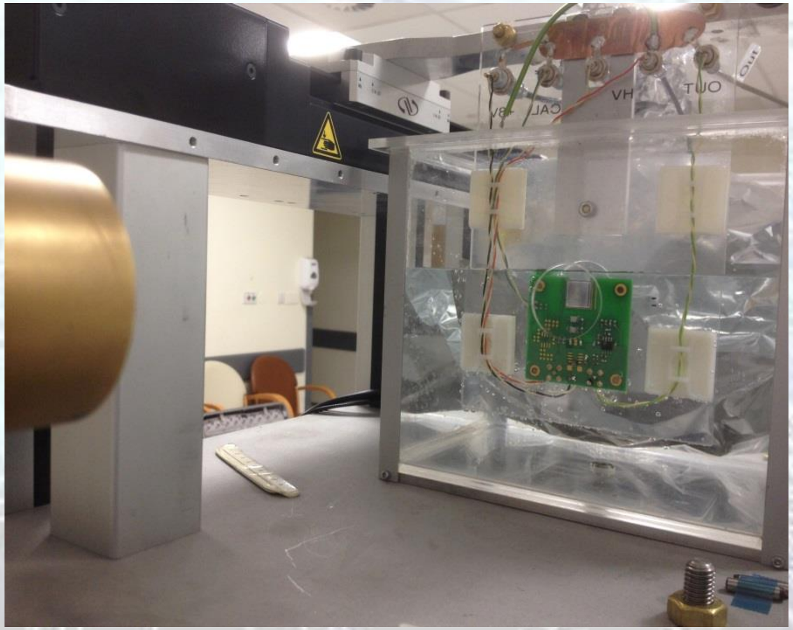
J. Taylor, G. Casse (University of Liverpool); A. Kacperek (Clatterbridge Centre for Oncology)

A silicon sensor is rapidly scanned through a tissue equivalent liquid to give the depth-dE/dx profile with high resolution. Silicon diodes (1D), and micro-strip detectors (2D) currently used. Ideally use a pixel to see full 3D dE/dx distribution for treatment planning and beam quality assurance.

Mechanical arm for mounting detector and read-out boards



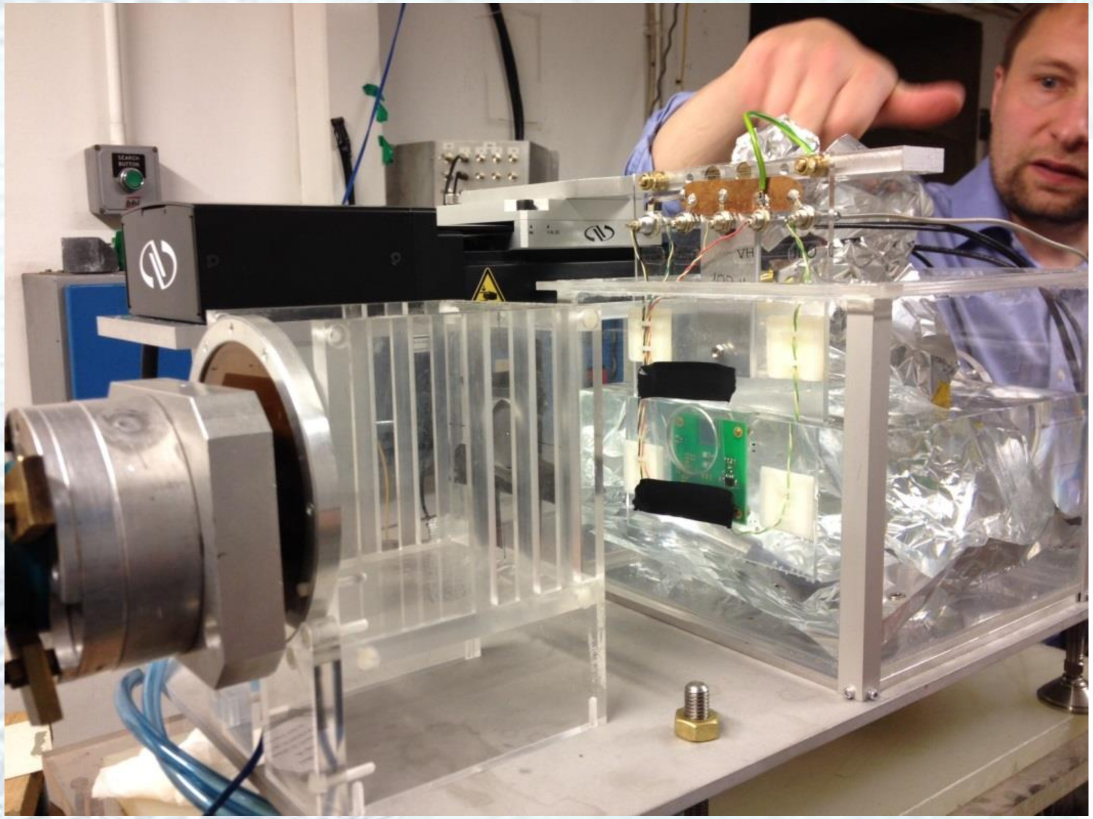




Water Phantom Measurements at Birmingham

Tony Price, David Parker, Stuart Green, Phil Allport (Birmingham)
Jon Taylor, Ilya Tsurin, Gianluigi Casse, Tony Smith (Liverpool)

100μm thick silicon detectors with 50μm parylene coating as a water barrier allowing good calibration with depth



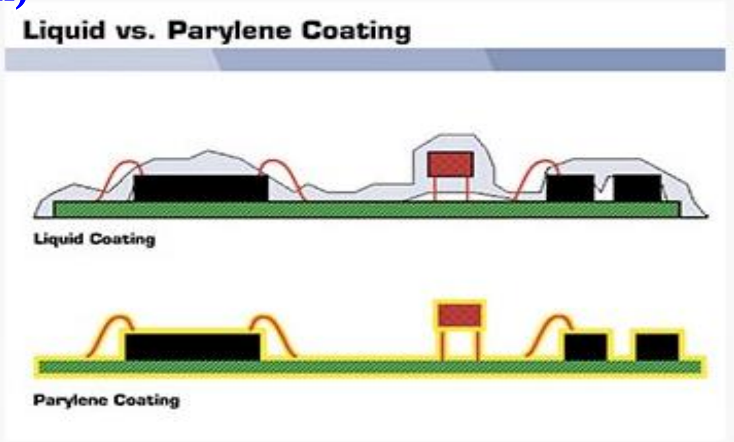
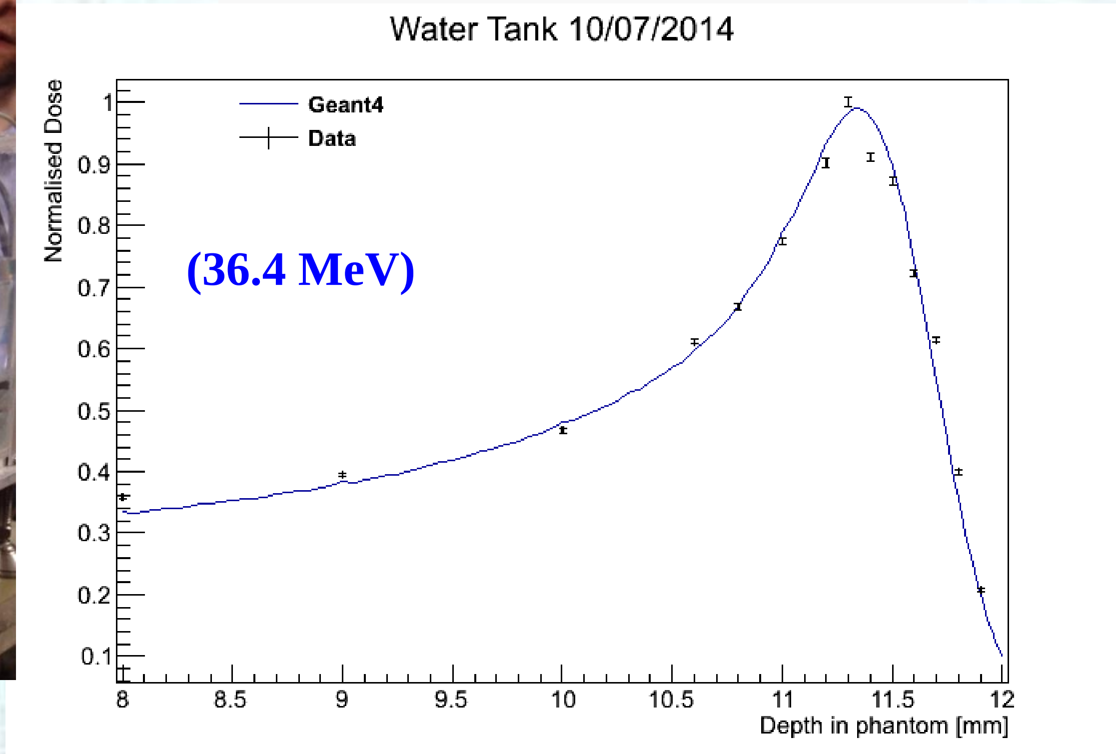


Illustration of liquid coating and Parylene coating



GEANT4 predictions including beam-line modelling

Proton Radiotherapy Verification and Dosimetry Applications

- **Integrated beam monitoring, computed dosimetry and tomography instrumentation for proton therapy**
- **Supported by the Wellcome Trust Translation Award Scheme, grant 098285.**
- **Members from academia, industry, and the health service.**

ADVANCED PROTON SOLUTIONS INC
UNIVERSITY OF LINCOLN
UNIVERSITY OF BIRMINGHAM
UNIVERSITY OF SURREY
UNIVERSITY OF LIVERPOOL
University Hospitals Birmingham NHS Foundation Trust
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THE UNIVERSITY OF WARWICK
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- **One of only 22 projects across all of science and engineering selected for RS Summer Exhibition (http://sse.royalsociety.org/2014/) and winner of 2014 Innovation Award of the IET.**

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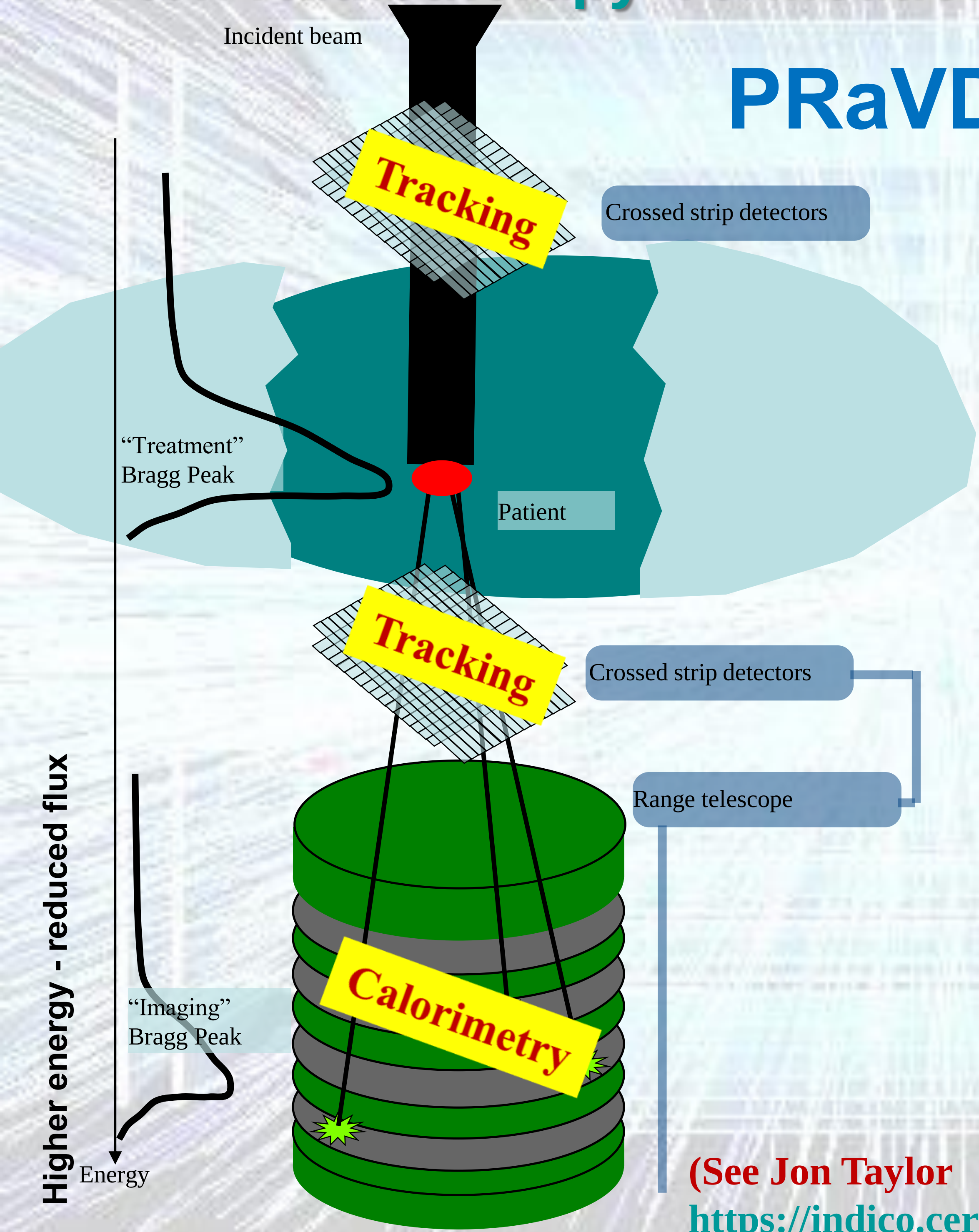
INNOVATION WINNER 2014

Proton Radiotherapy Verification and Dosimetry Applications

PRaVDA System Overview



Records beam position and profile in real-time to correct beam steering

Beam profile, particle flux for a given current and energy distribution can be routinely determined to cross-check delivery system calibration

With gantry movement permit full proton-Computed Tomography (pCT) scan using same particle type as for treatment.

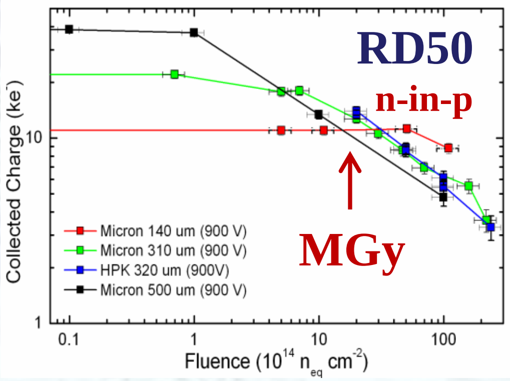
Current uncertainty in proton range is ~3.5%. If beam passes through 20cm of tissue, then Bragg peak could be anywhere within +/- 7 mm

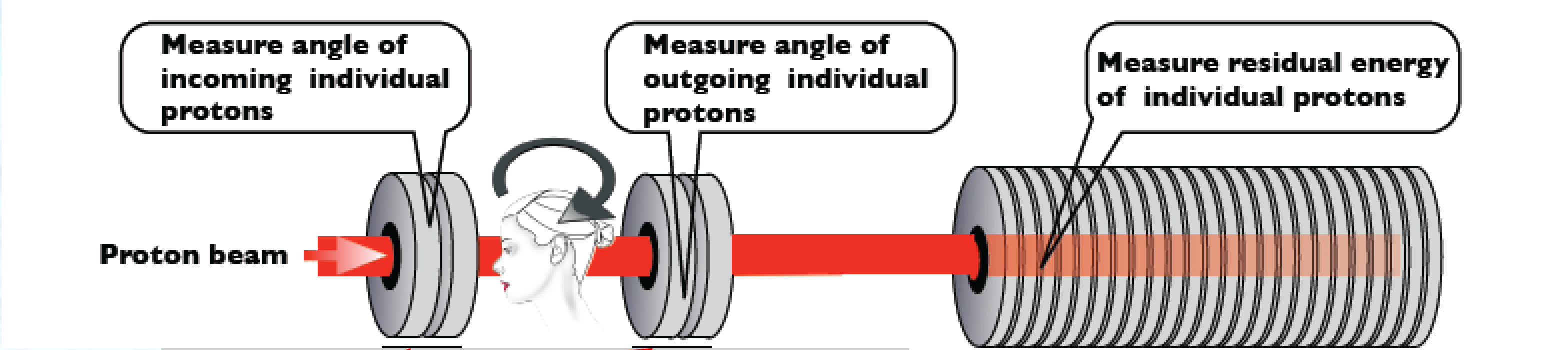
Aim to reduce proton range uncertainties to a ~1% – variation of +/- 2mm.

Simplified treatment plans – fewer beams; reduced probability of secondary cancers induced; and treatments will be shorter

(See Jon Taylor https://indico.cern.ch/event/340417/session/6/contribution/95)

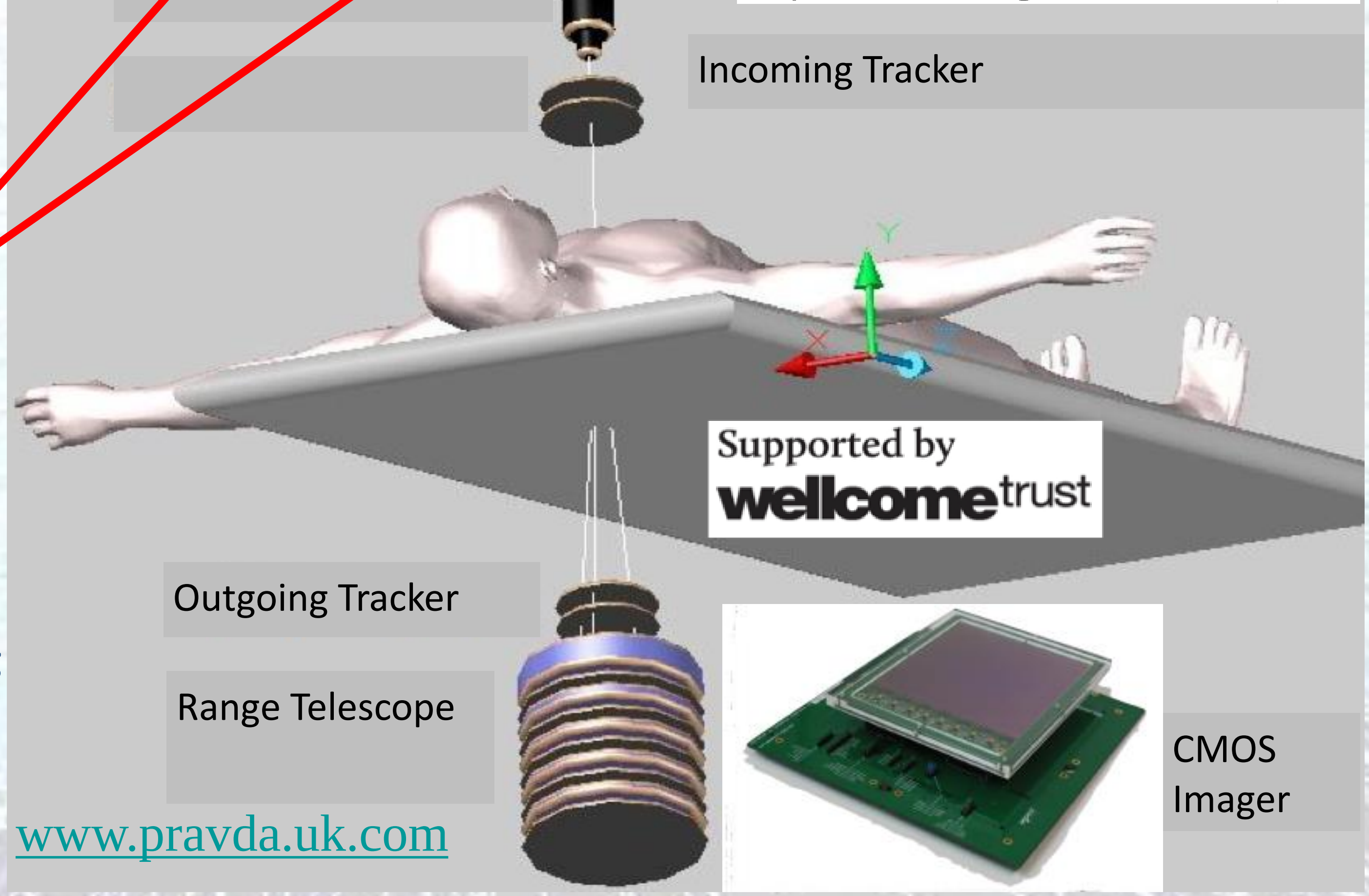
Proton Radiotherapy Verification and Dosimetry Applications





24 layers of radiation-hardened CMOS imagers.
Same basic technology used in mobile phone cameras, except over 500 times larger and work 20 times faster.

PRaVDA micro-strip detector



Silicon sensors with 2048 strips at 91µm pitch using 150µm thick n-in-p radiation-hard technology developed for High Luminosity LHC

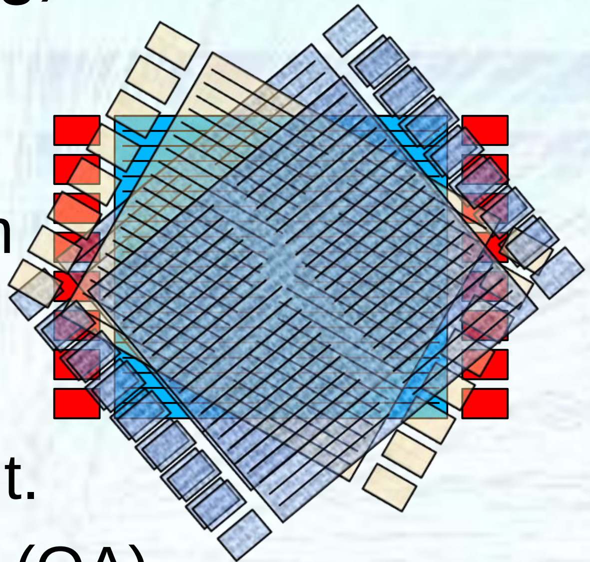
12 planes of strips used to make 4 tracking modules, 2 before and 2 after the patient

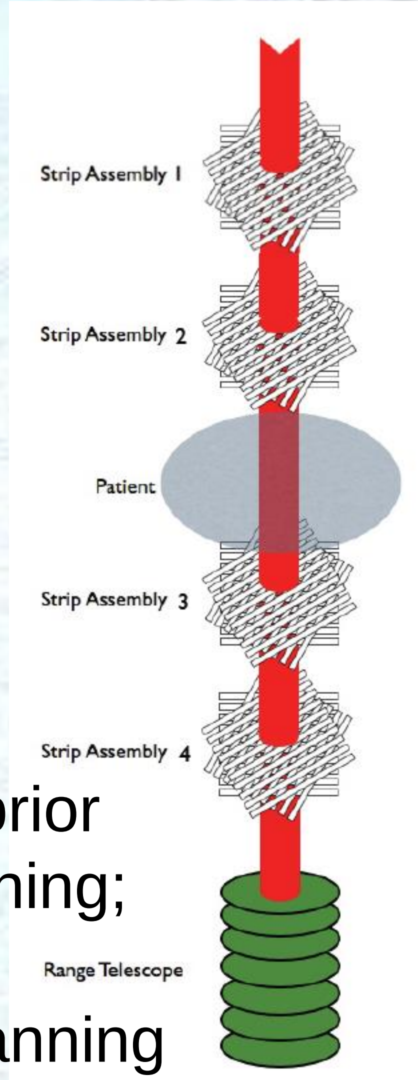
Each module of strips has three planes crossed at 60° in an (x,u,v) configuration to allow high particle rate

www.pravda.uk.com

Proton Radiotherapy Verification and Dosimetry Applications

- **PRaVDA targets beam monitoring, beam diagnostics and pCT**
- **In-treatment Beam monitoring.**
  - This can be employed when beam is being delivered to a patient.
  - Also when the treatment beam is being checked prior to treatment.
  - Useful for basic quality assurance (QA) of the proton beam during commissioning.



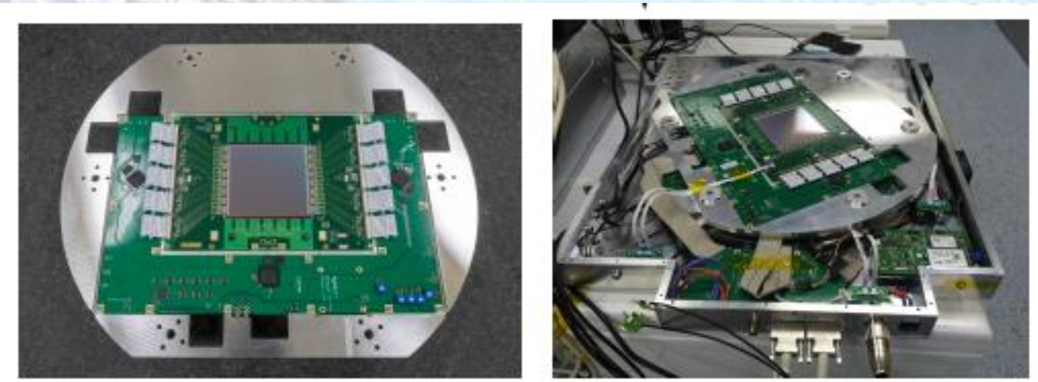


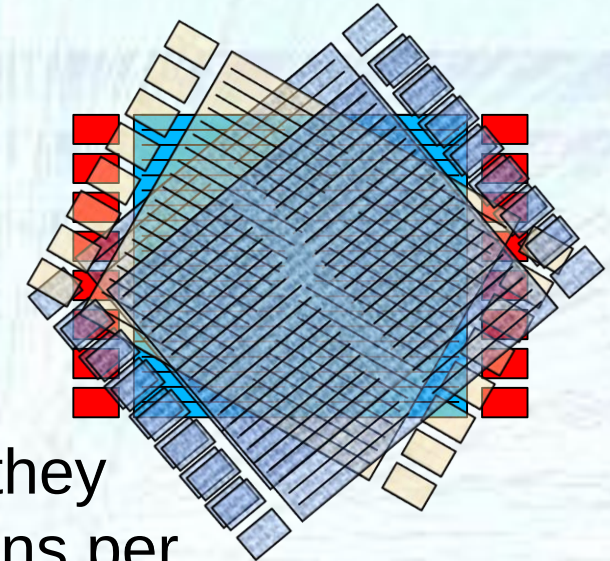
- **Patient Imaging.** This mode could be used several days prior to the first treatment fraction to obtain a CT image for planning; planar and CT imaging may also be used on treatment days for intra-fraction image-guidance or subsequent replanning
- Designed for **~10^5 protons/cm^2/s** and 39ns duty cycle (iThemba)

  Energies at IThemba up to **191 MeV**

  Collimation to 8.5cm diameter beam (not spot scanning mode)

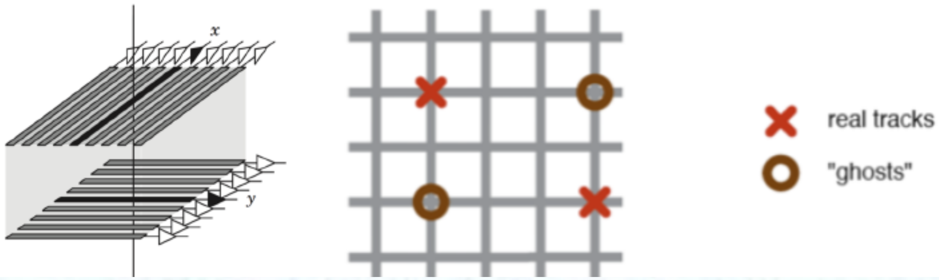
Proton Radiotherapy Verification and Dosimetry Applications

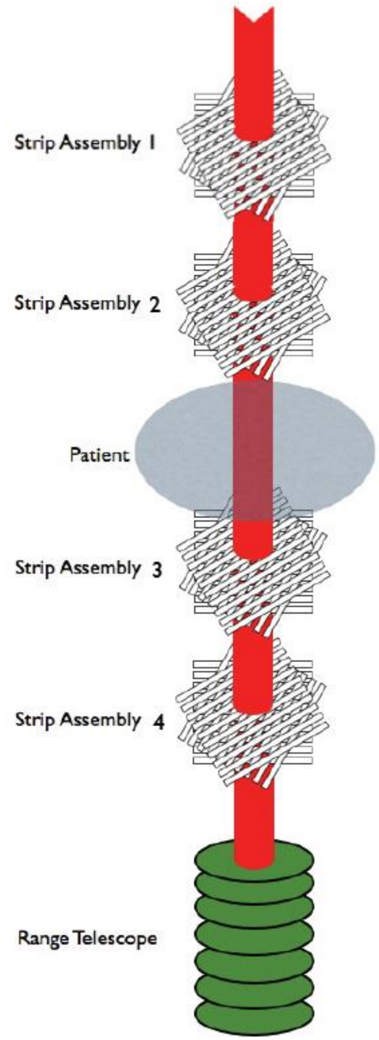




- **x-u-v:** A disadvantage of other systems with crossed strips is that they cannot cope with two or more protons per frame without ambiguities.

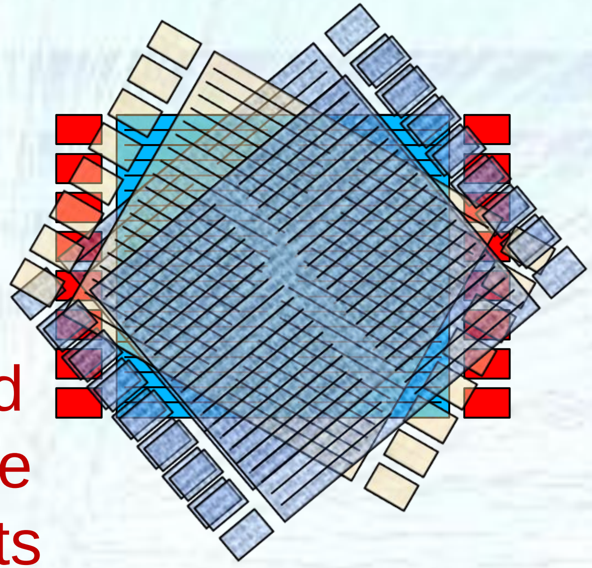
For a strip detector with orthogonal strips and N hits, there are: $N^2 - N$ 'Ghost-hits' or ambiguities generated

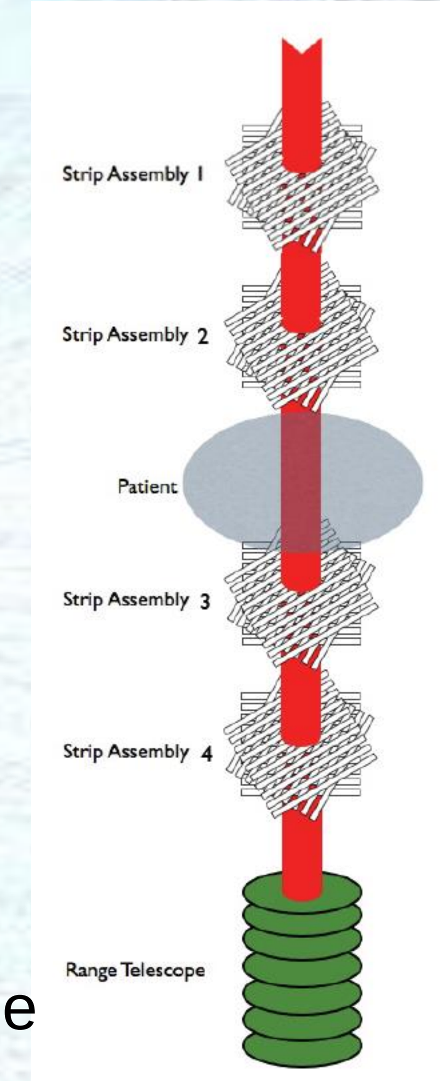




- The usual way round this with strips is to have a third layer **(3N Channels)**
- Depending on strip pitch, still problems above ~100 / frame
- Then need truly pixelated sensor, but needs to be fast **(N^2 Channels)**

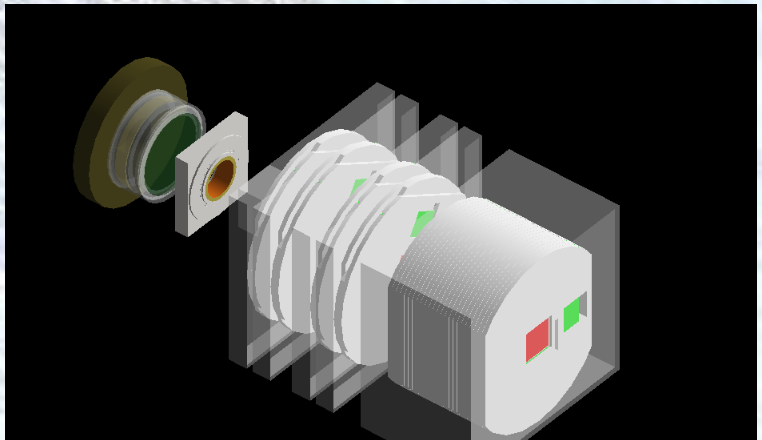
Proton Radiotherapy Verification and Dosimetry Applications



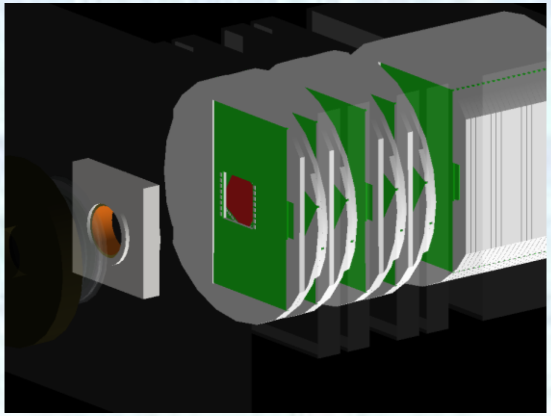


- **In-treatment Beam monitoring:**
- **10^7 protons/cm^2/s** at energies ranging from **60-191 MeV**
- Assuming 50cm^2 and 39ns would expect ~20 protons per frame
- At this rate ambiguities rates should still be negligible and 2D hits can be reconstructed but for higher currents could expect significant ambiguities but can still histogram 1D projections. (Can register double hits on strips as two thresholds can be set.)
- **Patient Imaging:**
- **10^5 protons/cm^2/s** in 39ns gives < 1 proton per duty cycle
- This is well within what can comfortably handled from an ambiguities perspective.
  The strip system would certainly cope with a higher data rate if there was sufficient read-out bandwidth.

Proton Radiotherapy Verification and Dosimetry Applications



iThemba beamline simulation developed by Cape Town University and PRaVDA simulation implemented by Tony Price (Birmingham).



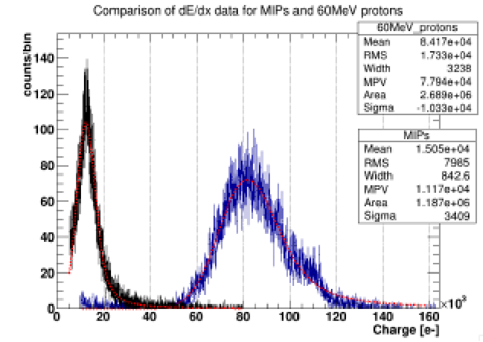
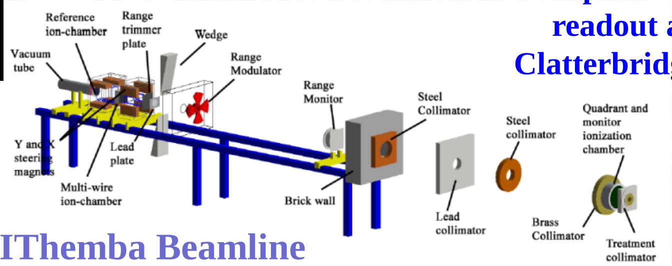
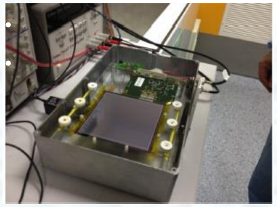


Figure 6. Energy loss of MIPs (black) and 60 MeV protons (blue) in a 155 μm PRaVDA detector.

Strip Tracker readout at Clatterbridge



iThemba Beamline



Proton tracking for medical imaging and dosimetry

J.T. Taylor,[a,1] P.P. Allport,[e] G.L. Casse,[a] N.A. Smith,[a] I. Tsurin,[a] N.M. Allinson,[b] M. Esposito,[b] A. Kacperek,[c] J. Nieto-Camero,[d] T. Price[e] and C. Waltham[b]

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[b] Laboratory of Vision Engineering, School of Computer Science, University of Lincoln, Lincoln, LN6 7TS, U.K.
[c] Douglas Cyclotron, The Clatterbridge Cancer Centre NHS Foundation Trust, Clatterbridge Road, Bebington, Wirral, CH63 4JY, U.K.
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Proton computed tomography reconstruction using a backprojection-then-filtering approach

G Poludniowski[1,3], N M Allinson[2] and P M Evans[1]

[1] Centre for Vision Speech and Signal Processing, University of Surrey, Guildford, GU2 7XH, UK
[2] Laboratory of Vision Engineering, School of Computer Science, University of Lincoln, Brayford Pool, Lincoln, LN6 7TS, UK

Need to know momentum vector and entry point of each proton going into the patient and also momentum vector and exit point coming out. Need tracks plus incoming and outgoing energies

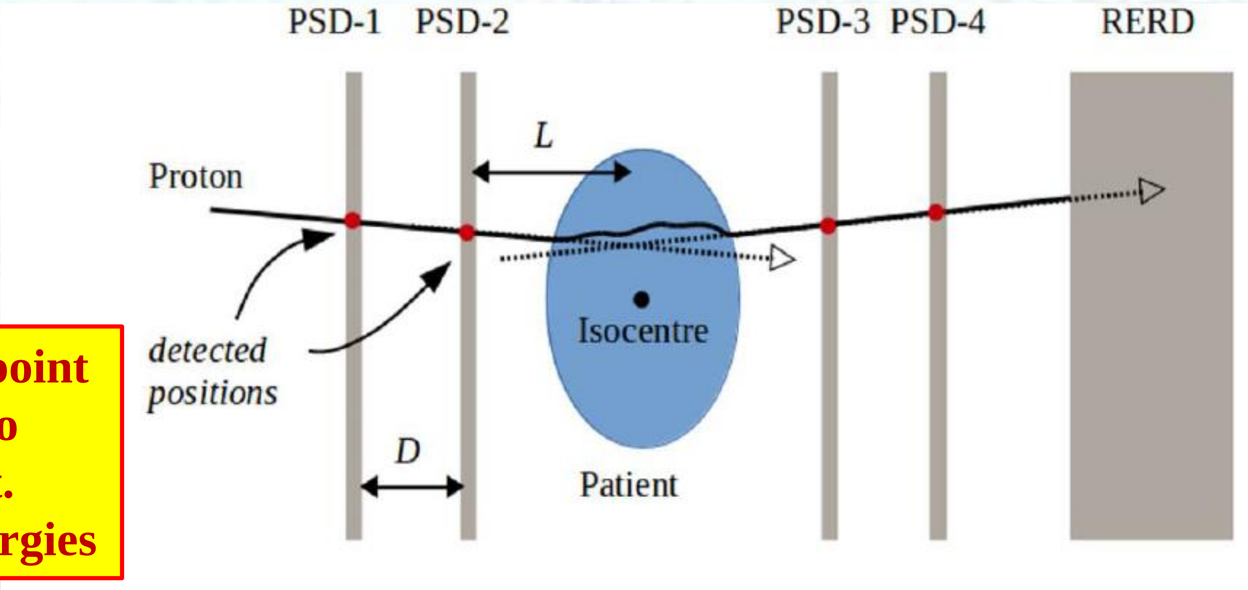

Figure 5. A schematic of the ideal proton-tracking pRG/pCT system.

Proton Radiotherapy Verification and Dosimetry Applications

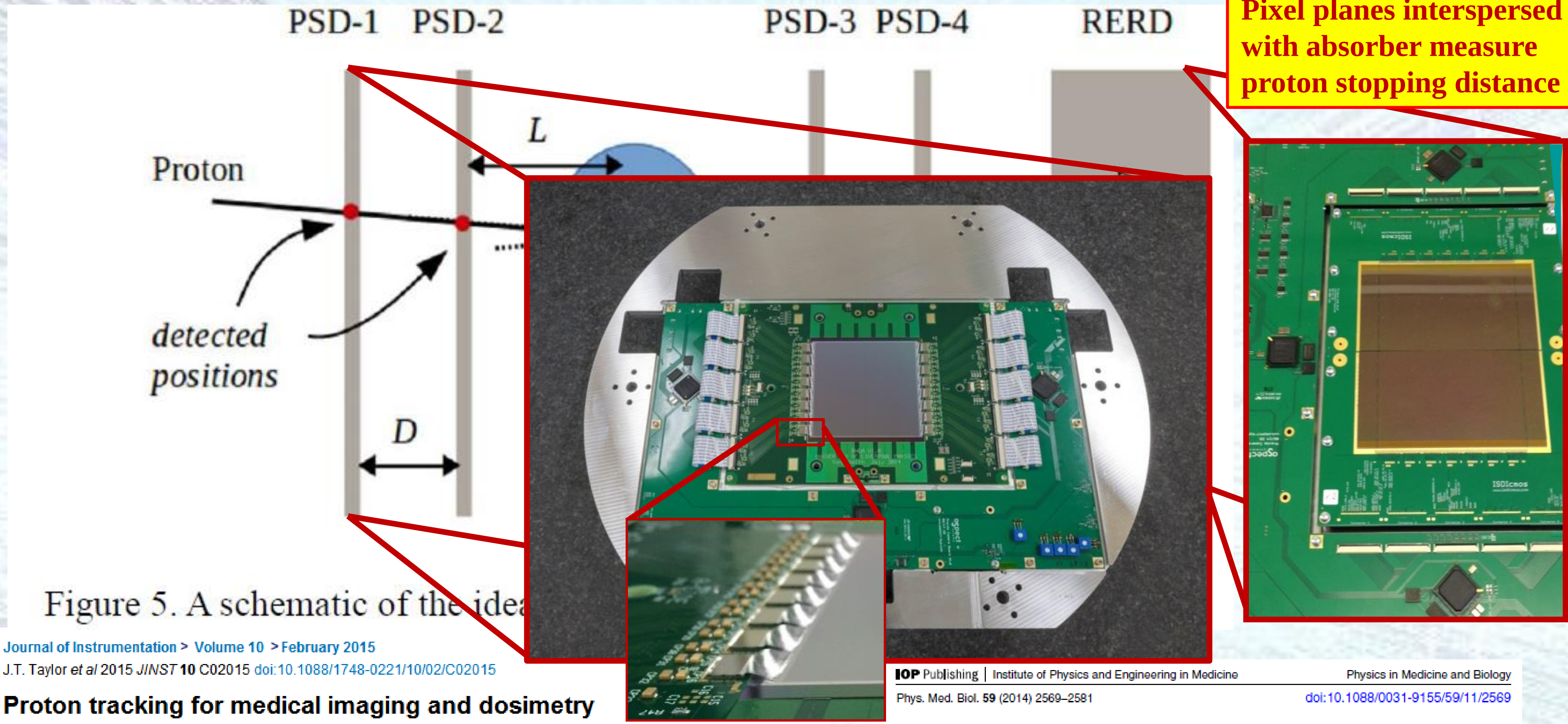

Figure 5. A schematic of the idea

Journal of Instrumentation > Volume 10 > February 2015

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Proton tracking for medical imaging and dosimetry

10TH INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS

J.T. Taylor[a], P.P. Allport[a], G.L. Casse[a], N.A. Smith[a], I. Tsurin[a], N.M. Allinson[b], M. Esposito[b], A. Kacperek[c], J. Nieto-Camero[d], T. Price[e] and C. Waltham[b]

Show affiliations

4 sets of 3 silicon strip planes reading out at the duty cycle of the cyclotron

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Phys. Med. Biol. **59** (2014) 2569–2581 doi:10.1088/0031-9155/59/11/2569

Proton-counting radiography for proton therapy: a proof of principle using CMOS APS technology

G Poludniowski[1], N M Allinson[2], T Anaxagoras[3], M Esposito[1,2], S Green[4,5], S Manolopoulos[6], J Nieto-Camero[7], D J Parker[4], T Price[4,5] and P M Evans[1]

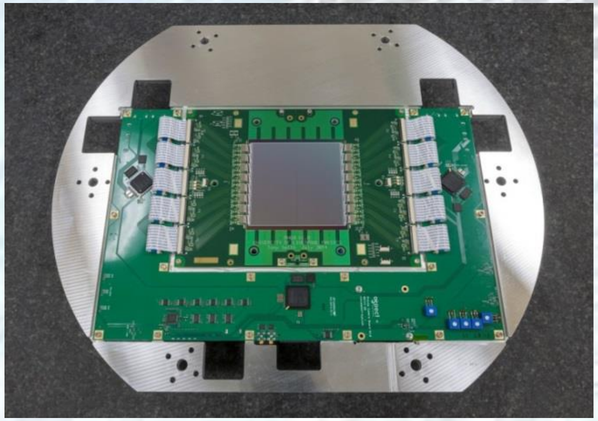
Proton Radiotherapy Verification and Dosimetry Applications

Tracker units tested extensively at Birmingham cyclotron with beams of 29MeV and 36 MeV protons.

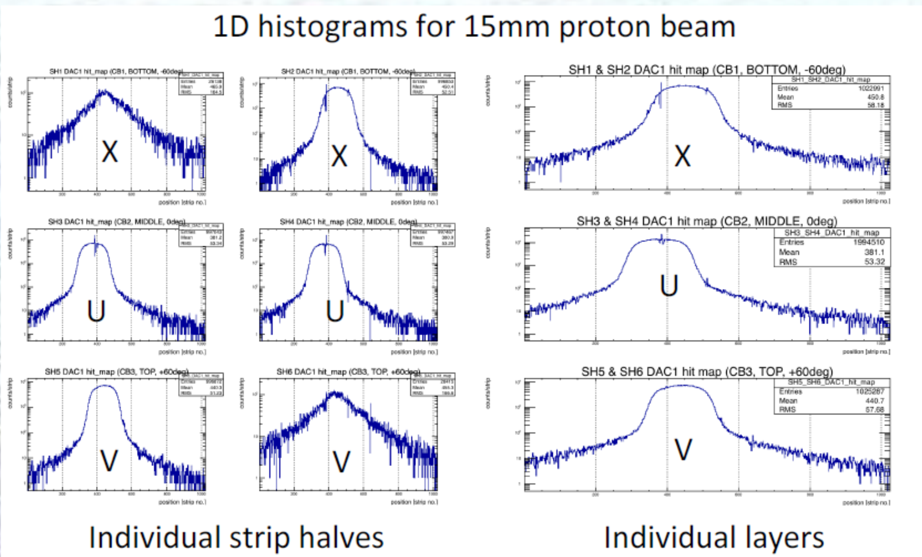
Currents from 10pA-10nA used which for 50mm beam corresponds to 5×10^3 - 5×10^6 protons/cm^2/s

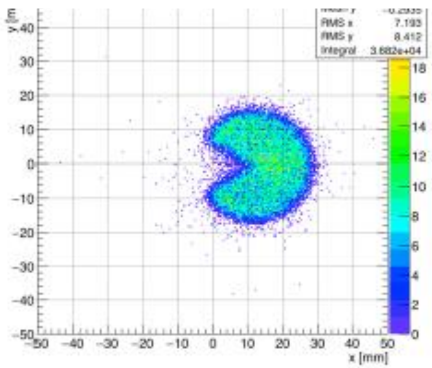
Radiation tested to >2kGy

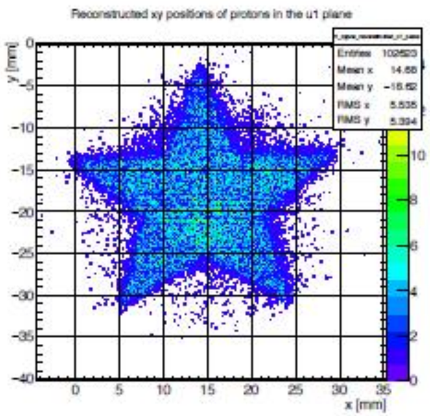
26MHz RF used for trigger

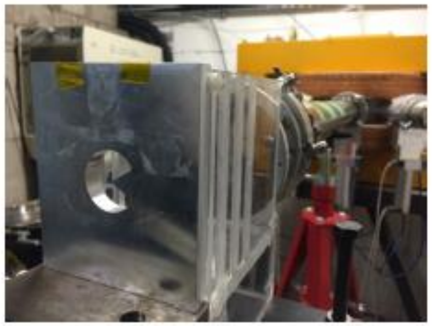


All 12 tracker planes completed and used in beam at IThemba

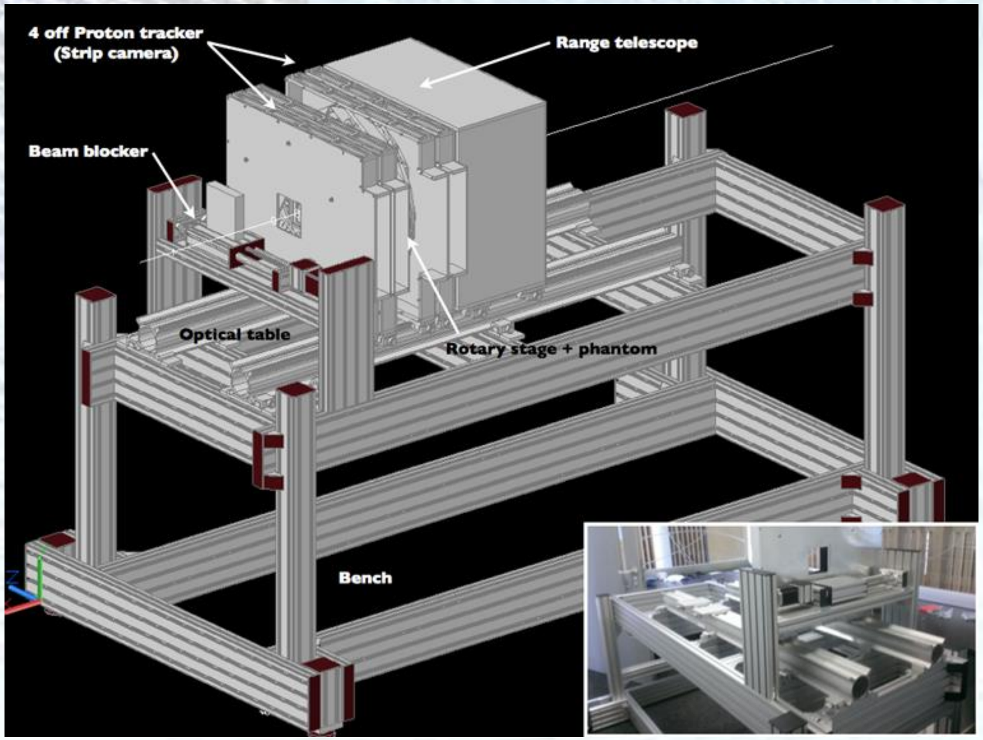


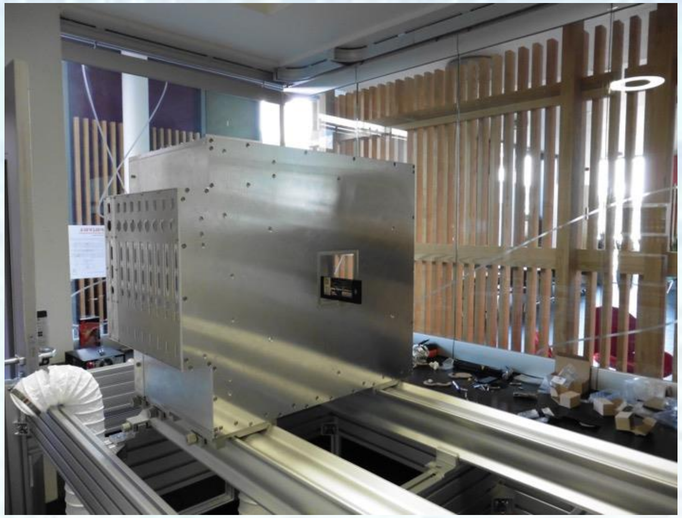


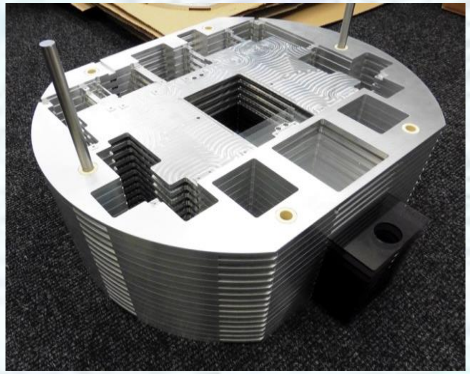




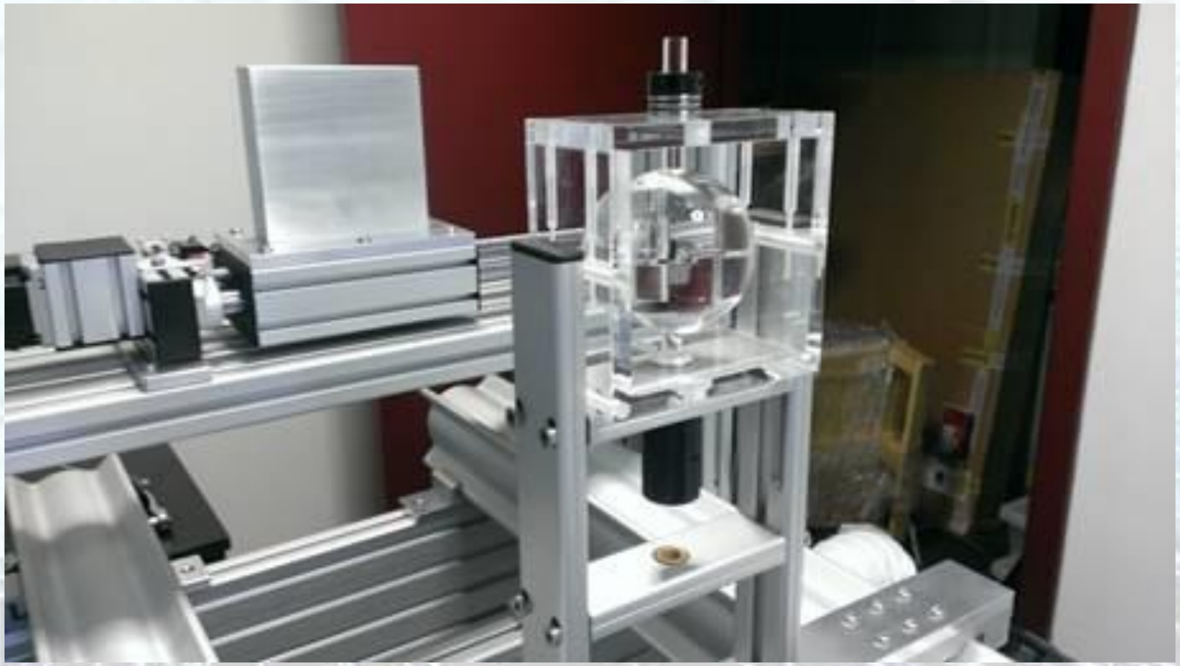
Proton Radiotherapy Verification and Dosimetry Applications







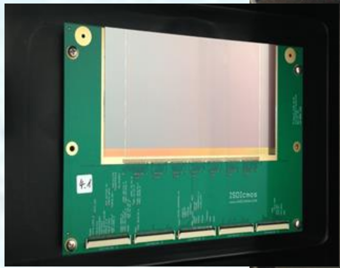
Mechanics, cooling and phantom design and manufacture, University of Lincoln

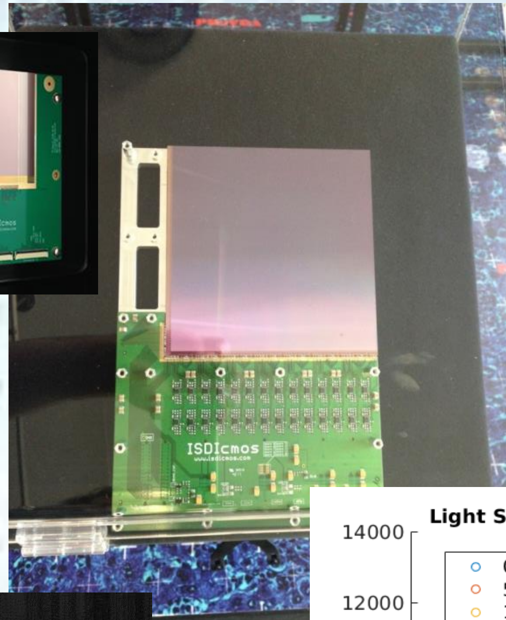


Proton Radiotherapy Verification and Dosimetry Applications

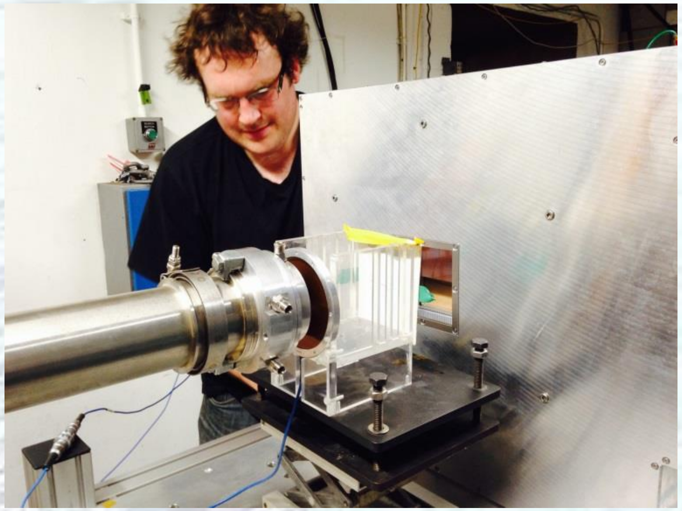
Monolithic Active Pixel Sensor (MAPS) parameters:

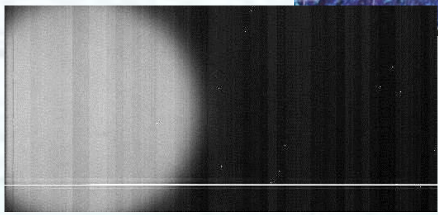
- Active area of 50 x 100 mm^2
- Pixel pitch of 194 x 194 μm^2
- Epitaxial layer thickness 18 μm
- Total wafer thickness 750 μm
- 0.35 μm CMOS Active Pixel Sensor
- 8-14 bit programmable ADC
- Rolling shutter read out at > 1000 fps
- ROI readout available
- 3 sides buttable



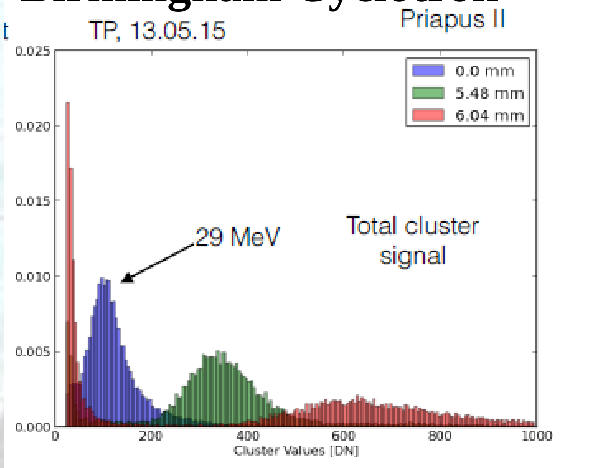


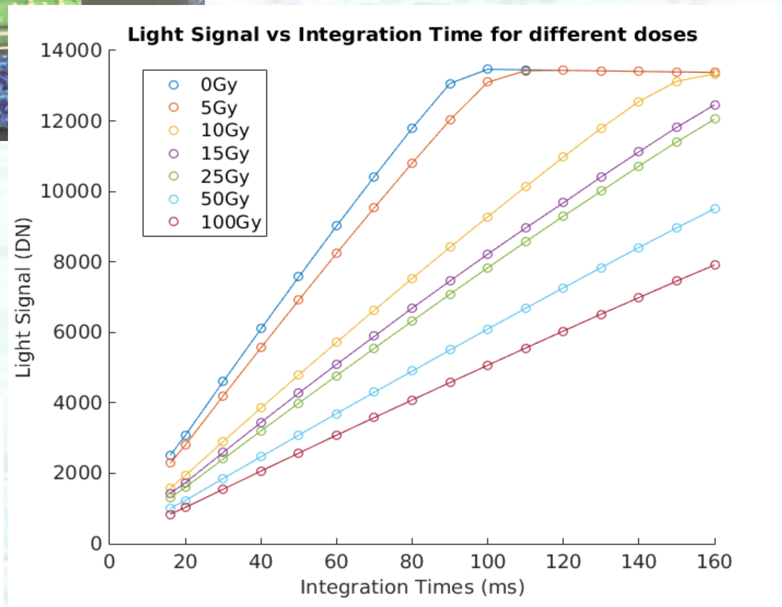
Ideally have 24 planes interspersed with thin absorber to measure stopping distance of each proton extrapolated to the range telescope by the tracking layers





MAPS beam image at Birmingham Cyclotron

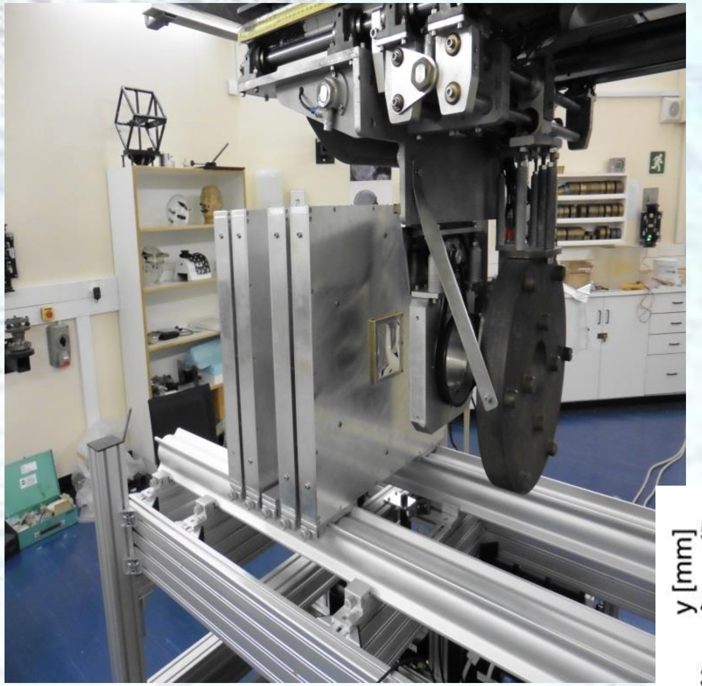


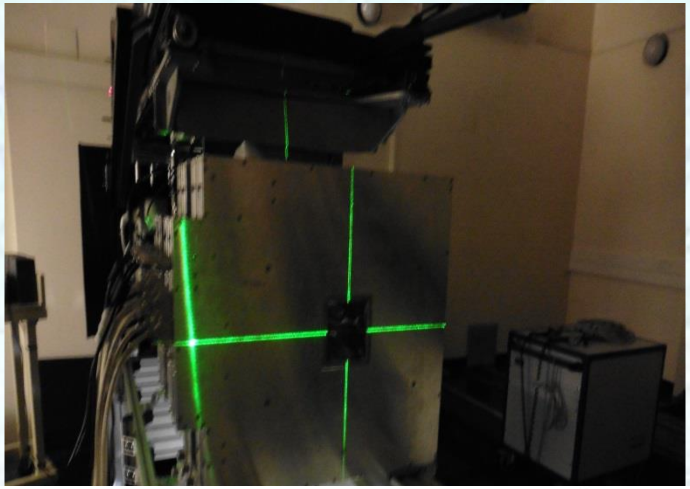


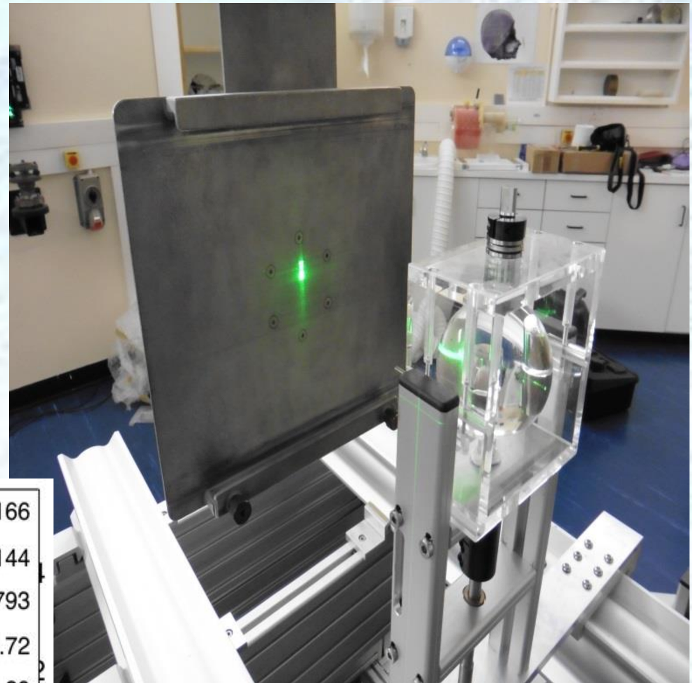
Radiation-hardness needs enhancing
Signal/noise OK at lower energies
New batch delivered end of 2015 and currently under evaluation

Proton Radiotherapy Verification and Dosimetry Applications

Latest News from IThemba (see http://www.pravda.uk.com/)

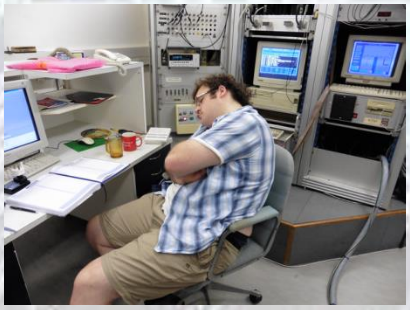


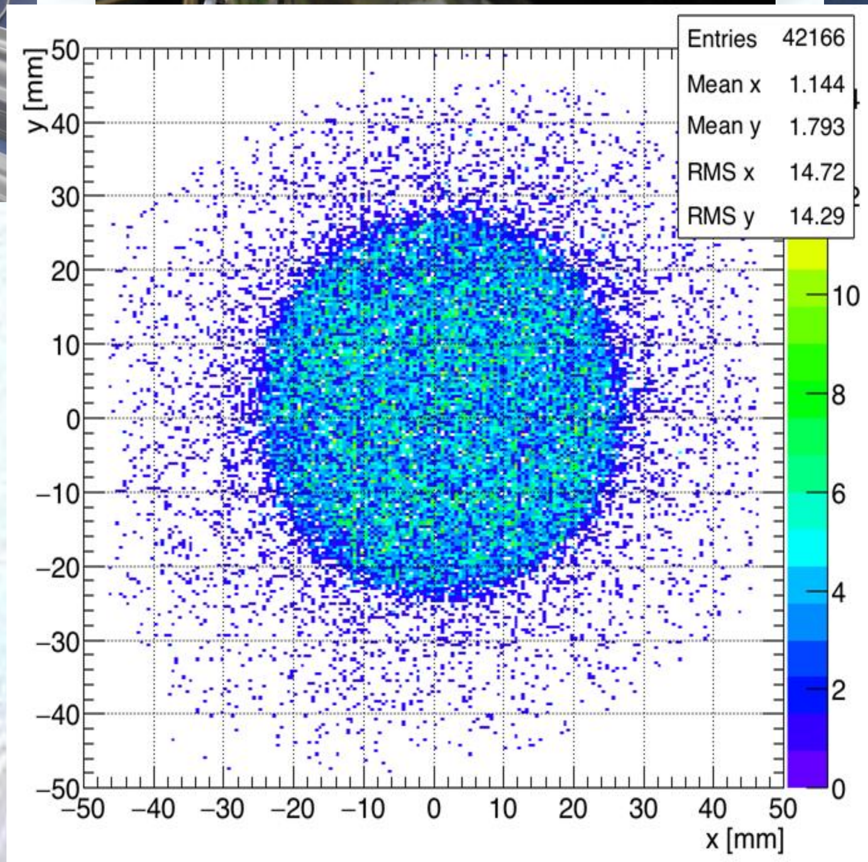




Highly successful run in November 2015 at IThemba with full strip tracker.

Data currently being analysed as team recovers from some long shifts



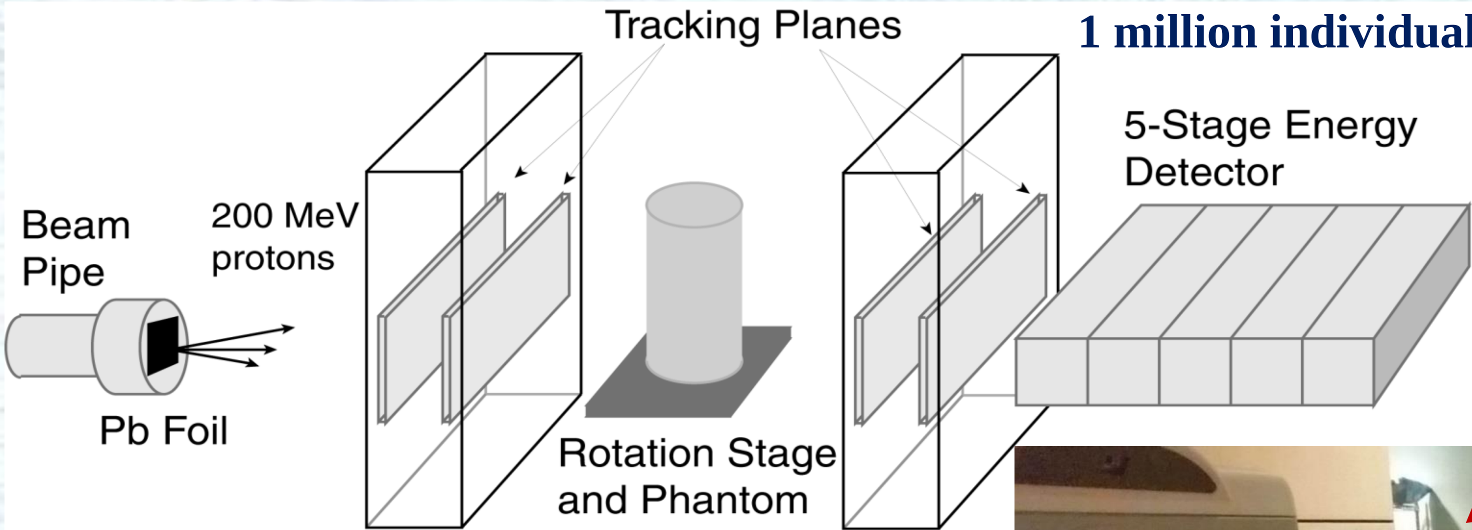


First Image of 5 cm diameter 191 MeV proton beam using four synchronised silicon strip trackers

The pCT Collaboration

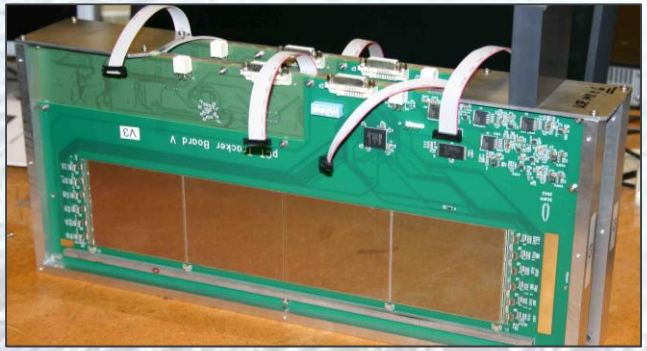
R. P. Johnson, Tia Plautz, Hartmut F.-W. Sadrozinski, A. Zatserklyaniy: ***SCIPP, U.C. Santa Cruz, Santa Cruz, CA , USA***
V. Bashkirov, V. Giacometti, F. Hurley, P. Piersimoni, R. Schulte: ***Division of Radiation Research, Loma Linda University, CA, USA***
P. Karbasi, K. Schubert, B.Schultze: ***Baylor University, Waco, TX, USA***

See Mondays talk at this Workshop by Reinhard and also the presentation by Hartmut Sadrozinski at
https://indico.cern.ch/event/340417/session/16/contribution/4/attachments/1160640/1670929/HSTD10-pCT_Poster-2.pptx



1 million individual protons reconstructed per second

H.F.-W. Sadrozinski, et al, *Development of a Head Scanner for Proton CT*, Nucl. Instr. Meth. A 699 (2013) 205.

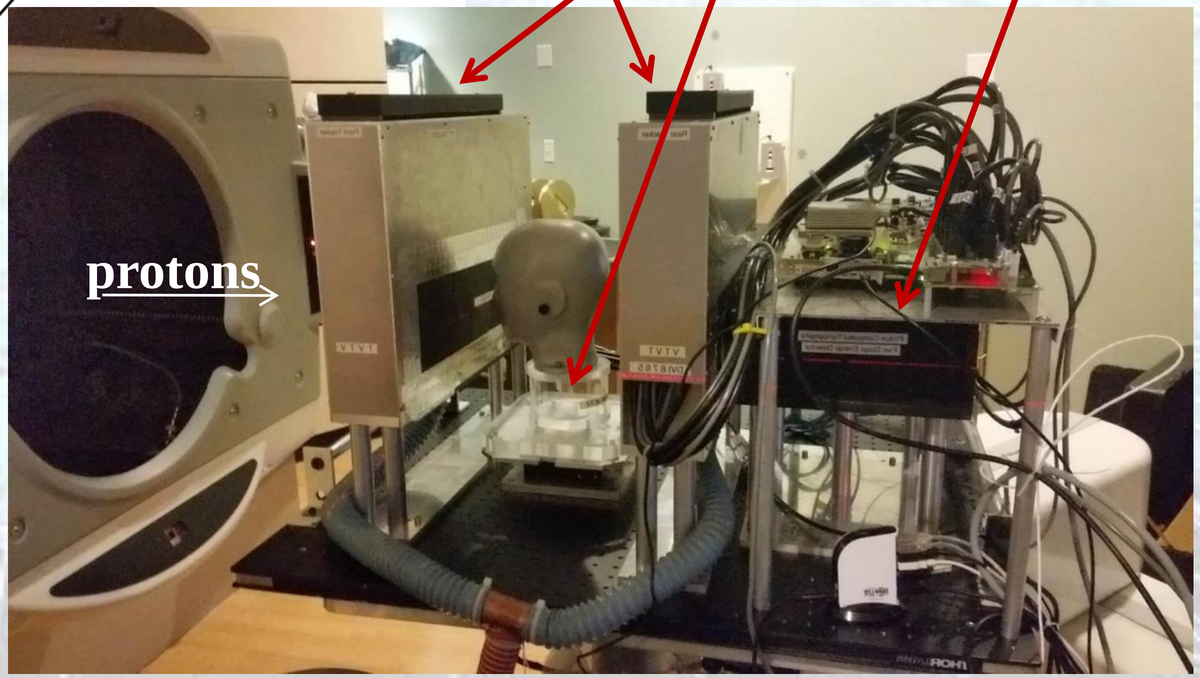


Four 9cm*9cm silicon strip sensors with thin-edge technology in x-y configuration

Rotation Stage

5-Stage Energy Detector

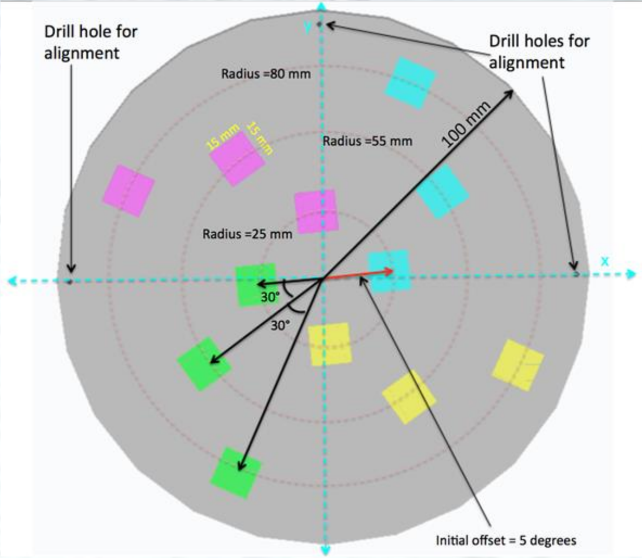
Trackers

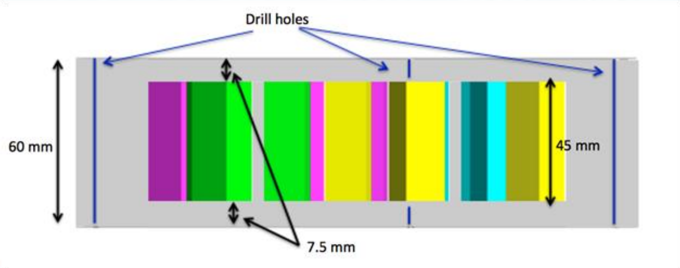


The pCT Collaboration

Spatial Resolution Studies: Edge Phantom

A phantom was designed and fabricated for the purpose of measuring a **modulation transfer function (MTF)**





Left: Top down view of the Edge Phantom.
Right: Side view of the Edge Phantom

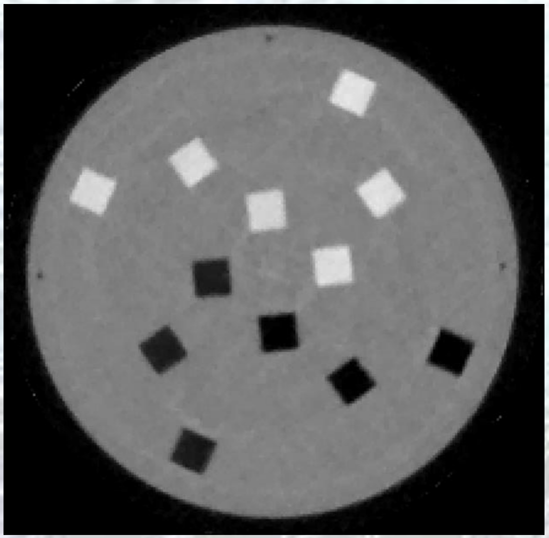
Cyan: Tooth Enamel
ρ = 2.04 g/cm^3; RSP = 1.784
Magenta: Cortical Bone
ρ ~ 1.91 g/cm^3; RSP = 1.699

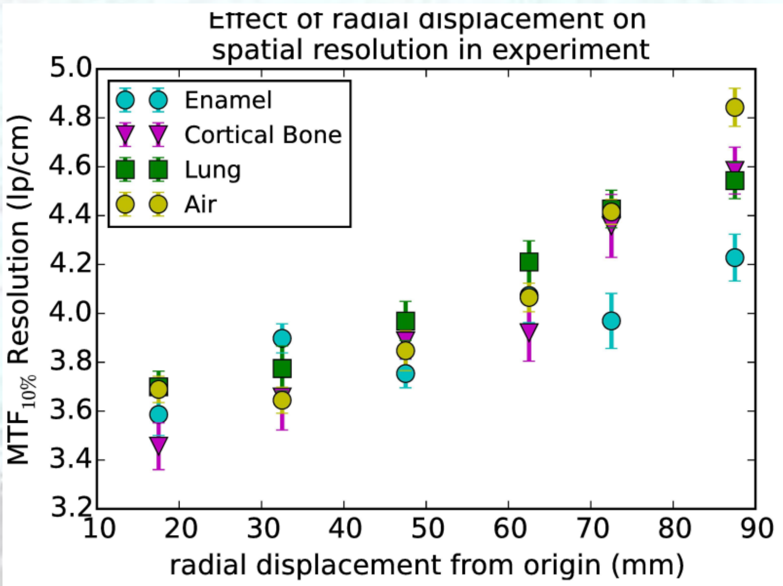
Green: Lung
ρ ~ 0.205 g/cm^3; RSP = 0.203
Yellow: Air
ρ = 0.0012 g/cm^3; RSP = 1.06e-03

MTF is the function of relative modulation with respect to spatial frequency (lp/cm) that characterizes the resolution of an imaging system.

Water Equivalent Path Lengths measured using stepped pyramids of polystyrene blocks show each proton can be reconstructed to an rms precision of ~<u>3 mm</u>

7 min continuous scan (1 rev/min), 150 Million histories, 1 mm x 1 mm x 1 mm voxel size, 1 deg angular bin size.

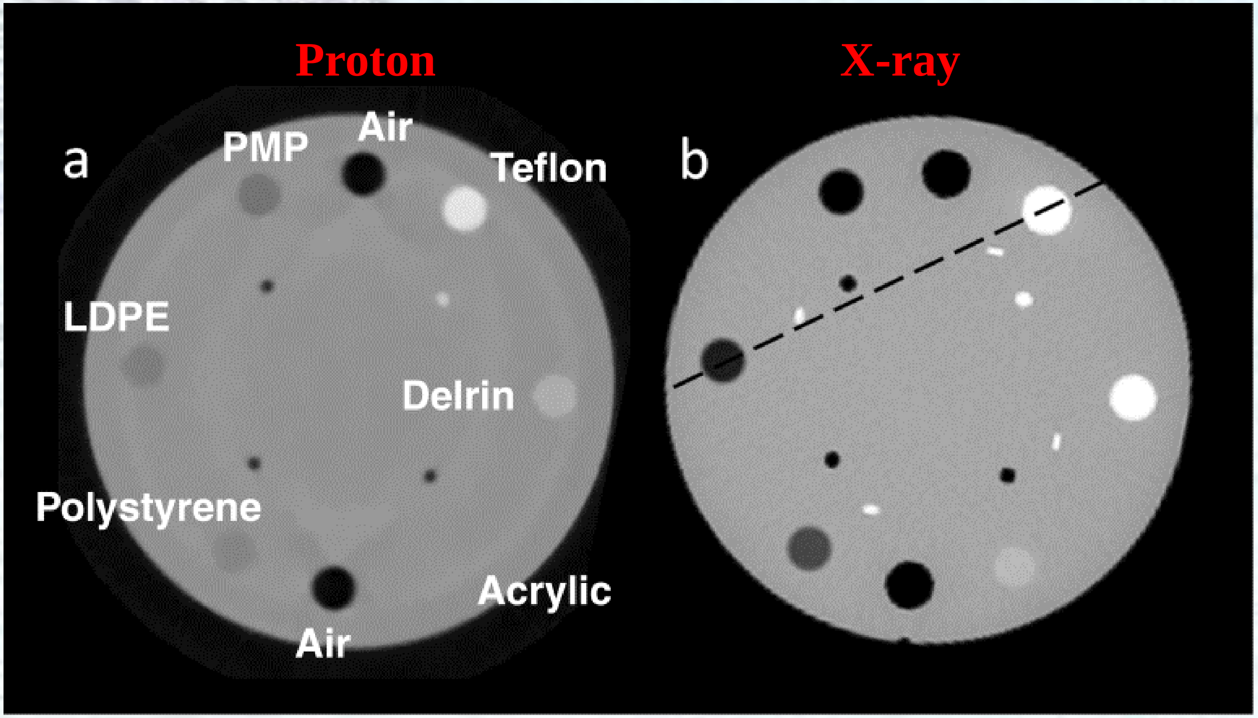


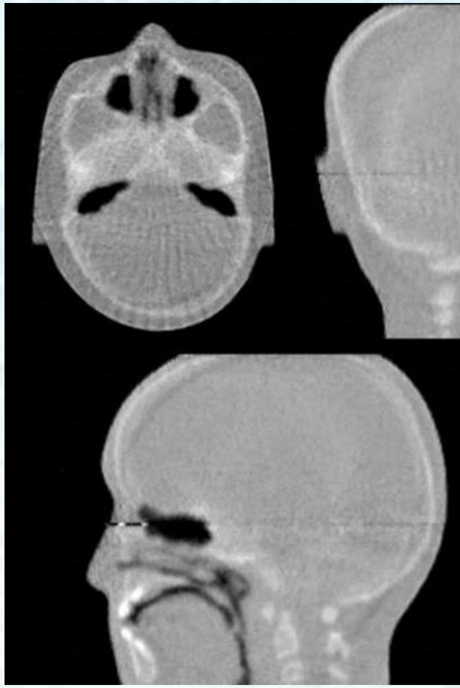


Spatial Resolution
is close to maximum (for 1mm pixels the Nyquist frequency is 5 lp/cm).

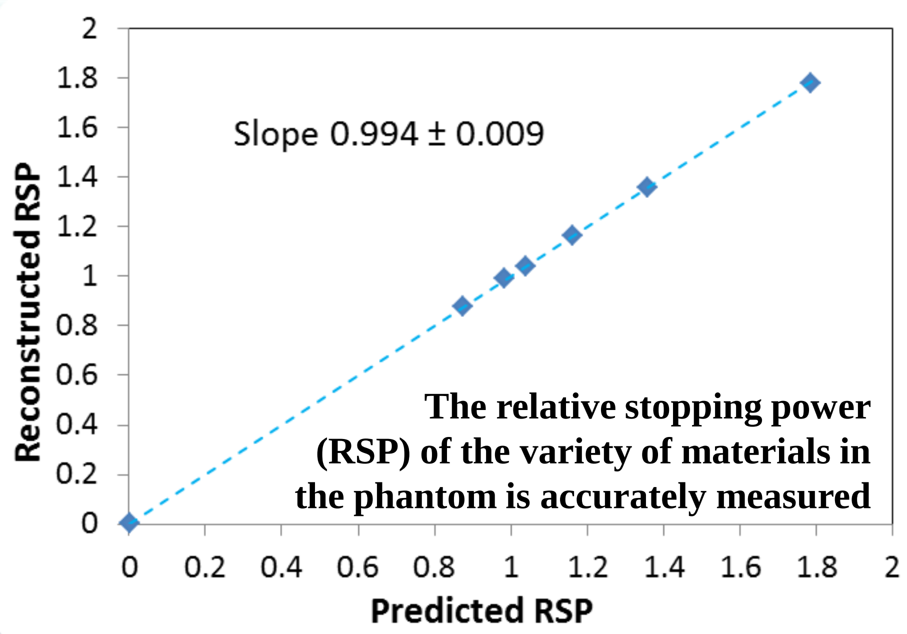
MTF varies as a function of radius by ± 10-20%.

The pCT Collaboration



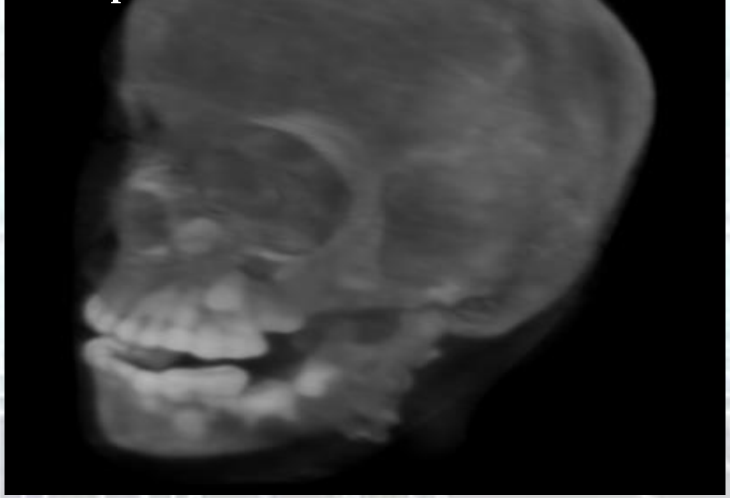


Three cardinal planes of 3D RSP images obtained with Phase II scans of the anthropomorphic head phantom.



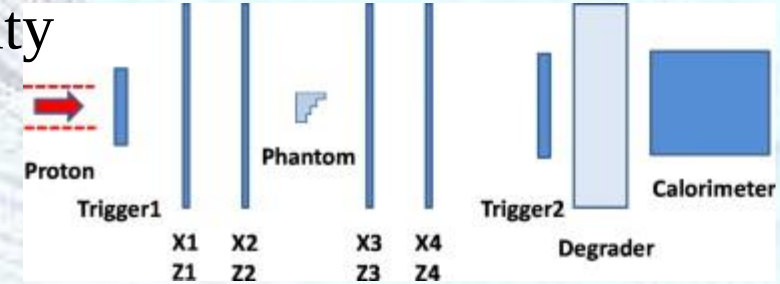
The relative stopping power (RSP) of the variety of materials in the phantom is accurately measured

3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom

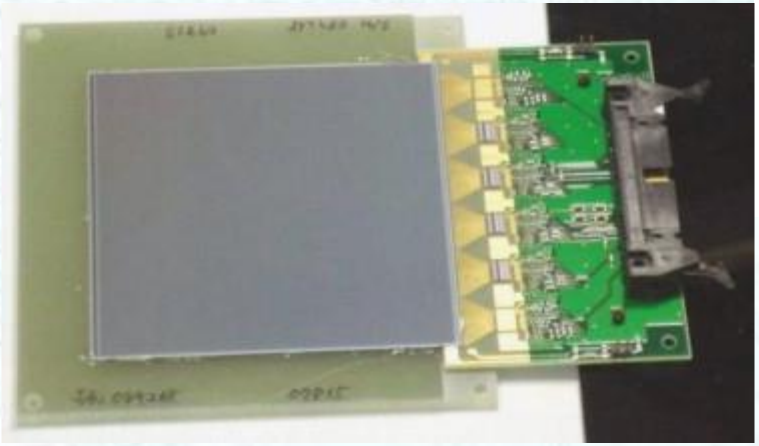


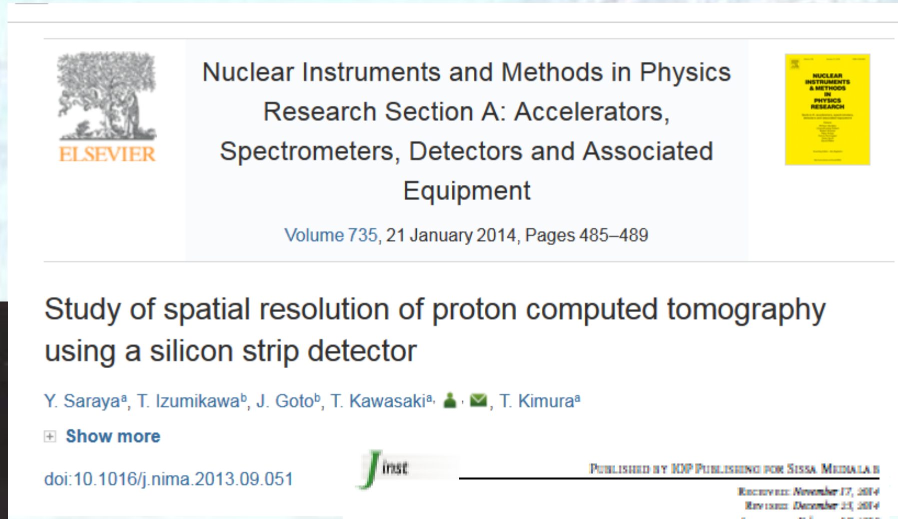
Some Other Activities

- Another group using similar sensors to the pCT Collaboration is based at Niigata University



Item	Specifications
Outer dimensions	89.5×89.5 mm^2
Active area	87.6×87.6 mm^2
Substrate thickness	410±10μm
Strip pitch	228μm
Readout pitch	456μm
Number of strips	384
Full depletion voltage	<120<120 V





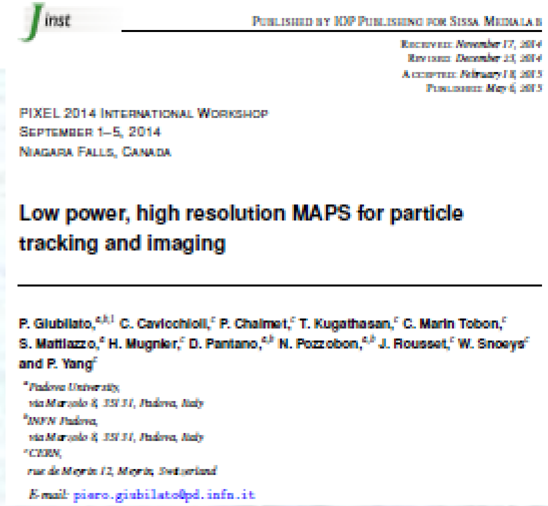
ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 735, 21 January 2014, Pages 485–489

Study of spatial resolution of proton computed tomography using a silicon strip detector

Y. Saraya[a], T. Izumikawa[b], J. Goto[b], T. Kawasaki[a], T. Kimura[a]

Show more

doi:10.1016/j.nima.2013.09.051



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PIXEL 2014 International Workshop
September 1–5, 2014
Niagara Falls, Canada

Low power, high resolution MAPS for particle tracking and imaging

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- A very promising approach being followed by Padua with CERN is the use of MAPS technologies for the tracking but with intelligent on-chip data sparsification to deliver faster, low power readout
- There are a number of other initiatives using different tracking technologies, scintillating fibres, multi-wire proportional chambers, … all of which have potential advantages and disadvantages when compared with silicon detectors

Conclusions

- The particle physics community has over 40 years of experience of operating finely segmented silicon sensors for precision tracking of charged particles in high rate, high radiation environments
- In developing these radiation-hard detectors, we have seen a possible application for sensors which would need to sit permanently in a hadron beam for years without any need to recalibrate for change in signal with dose
- Large area Monolithic Active Pixel Sensors have been developed for PRaVDA range telescope but speed and radiation-hardness need improving. (Developments in HV-CMOS and HR-CMOS could allow common pixel technology throughout)
- A number of consortia are investigating ways to use both tracking and energy measuring technologies from particle physics and other fields in support of hadron therapy facilities. (PRaVDA and pCT discussed here as examples using silicon detectors; apologies for not covering the many other international activities.)
- Accurately tracking the path of protons will be of value to future hadron therapy facilities not only for beam monitoring and diagnostics, but also as providing the exciting possibility of pCT to even better improve accuracy for treatment

Thank you for your attention

pCT Data Acquisition (DAQ) Flow

The readout is triggered, for ease of synchronization and event building, with ample buffering at the front end to minimize dead time. Eight layers of silicon strip detectors are read out by 144 64-channel ICs, each with a 100 Mbit/s link to an FPGA on the same board. Similarly, each of the two energy detector boards includes an FPGA. The 14 front-end Spartan-6 FPGAs build the local event data and then send it over dual-link DVI-D cables to the Virtex-6 FPGA, which builds the complete event and then sends it by Ethernet to a computer that is running a custom Python-coded DAQ program.